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(54) Title: METHOD, COMPUTER PROGRAM PRODCUT AND USE OF A COMPUTER PROGRAM FOR STABILIZING A MULTIPHASE FLOW

(57) Abstract: The present invention relates to a method for stabilizating multiphase flow through a pipeline, riser or well flow line (8a), characterized by implementation of a dynamic feedback controller (9) by controlling a control valve or choke (2) at the outlet (13) of the pipeline or riser (8a).

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Method, computer program product and use of a computer program for
stabilizing a multiphase flow.

FIELD OF THE INVENTION

The present invention relates to a method for applying a
5   dynamic feedback controller to stabilize multiphase flow in
a flow line, such as a pipeline, riser or well production
line, where slugs cause instability of the multiphase flow.
The invention also relates to a computer program product,
which carries out the steps of the method.

10   BACKGROUND OF THE INVENTION
Oil that is produced offshore is transported through
pipelines as a complex mixture of oil, gas water and sand.
One common flow regime is known as slug flow, in which the
mixture flows intermittently along the pipelines and
15   comprises a concentrated mass in the form of a liquid plug.
Such a concentrated mass in movement is hereafter called a
slug.

In multiphase pipelines/risers/well flow lines at reduced
flow rates and/or changing gas oil ratio, compared to
20   design specifications, instabilities in terms of terrain-
induced and riser-induced slug flow often occur. Such a
slug flow is a bulk of liquid moving in the pipeline
followed by an amount of gas.

Terrain and riser-induced slug flow is often referred to as
25   severe slugging. A publication by Yehuda Taitel, "Stability
of Severe Slugging", Int. Journal of Multiphase Flow, Vol.
12, No. 2, pp. 203-217, 1986, describes the phenomena of
slugging. Terrain and riser-induced slug flow is induced
periodically as liquid in terms of oil and water is
30   accumulated in lower parts of the pipeline/riser, see
Figure 11-IV. At a certain time the liquid will restrict
the passage for the gas. In this situation a small amount
of gas bubbles through the liquid plug, however the main
part of the gas accumulates upstream of the liquid plug
35   which causes the pressure to increase (see Figure 11-I). In
this situation the pressure upstream of the liquid plug is

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equal to the pressure downstream of the liquid plug plus
the hydraulic pressure across the liquid plug (applying a
static force balance). But when the pressure increase
upstream of the liquid plug becomes larger than the
5   pressure increase downstream the liquid plug, the liquid
plug starts moving (see Figure 11-II), and then forms a
slug, which accelerates. It should be noted that this
condition might be fulfilled before the front of the liquid
plug reaches the downstream maximum point in the pipeline
10   profile.

Depending on operating conditions and pipeline profile, the
slug may die out or it may be transported to the outlet of
the pipeline/riser. In a situation where the tail of the
liquid plug enters the vertical parts of the flow line
15   (Figure 11-III), a rapid increase in the liquid flow rate
occurs due to the unstable situation where the pressure
head, due to the liquid column, decreases. A slug is formed
and the slug get transported to the outlet of the pipeline,
and when the gas behind the slug escapes the
20   pipeline/riser, the remaining liquid in the vertical parts
returns to the bottom of the riser or dips in the pipeline
profile. Then the whole process is repeated, and the result
is an unstable multiphase flow pattern/cycle where the
liquid flow rate varies from zero to a significant value,
25   as the slug passes a fixed point in the pipeline, in a
short period of time. The flow pattern is characteristic of
severe slugging (terrain/riser-induced slugging). For
terrain-induced slug flow the corresponding liquid plugs
are caused by terrain effects reflected in the pipeline
30   profile (offshore and onshore), whereas riser induced slug
flow is caused by the pipeline leaving the seabed on its
way to the surface (offshore). For long risers, special
dynamic effects might occur due to phase transition from
liquid to gas due to a considerable pressure decrease in
35   the riser. Different riser shapes may also affect the
dynamics in riser-induced slugging.

Unstable flow causes considerable problems for production
in the upstream wells and operation of the downstream
processing plant:

- Large disturbances to the separator train, causing:

  5   o Limiting separation capacity due to the need for
           larger operating margin to achieve the desired
           separation.

           o Poor separation (water carry over to export
           pipeline) due to rapidly varying separator feed
 10   rates.

           o Poor separation results in varying quality of
           water outlet from separators, causing large
           problems in the downstream water treatment system
           and possible violation of environmental
 15   restrictions.

- Large and rapidly varying compressor loads, causing:

           o Inefficient compressor operation.

           o Limiting compression capacity due to the need for
           a larger margin to handle gas holdup behind the
 20   liquid.

           o Spurious flaring from limited compression
           capacity.

- Limited production from the upstream wells. The
           pressure variations at the pipeline or riser inlet 1
 25   are also visible in the upstream wells, resulting in
           limited production from wells suffering from reduced
           lifting capacity.

For gas lifted oil wells a problem referred to as casing
heading might occur. Applications of gas lifted oil wells
are different than slug flow in pipelines, risers and wells
in the following sense:

5   - The dynamic interactions in the casing heading are
between the casing (conducting the gas to the injection
point) and the tubing (flowline).

For gas lifted wells the gas injection rate (at some point)
can be utilized for control, which gives additional degree
10   of freedom.

There are four main categories of principles for avoiding
or reducing the effects of slug flow:

1. Design changes

2. Operational changes

15   3. Procedures

4. Control methods:

         - Feed forward control to separation unit

         - Slug choking

         - Active slug control

20   An example of a typical slug handling technique that
involves design changes is a technique that requires
installation of slug catchers (onshore). Such design
changes also have the disadvantage of that substantial
capital investment is needed. Another example of such a
25   technique is to increase the size of the first stage
separators to provide buffer capacity. For already existing
installations where problems with slug flow are present,

and for compact separation units, these design changes have limited effects on flow stability. Still, using this technique, compressors may trip due to large rapid variations in the feed rates to the separators caused by
5   unstable multiphase flow.

An example of an operational change is to choke the pipeline to such an extent that the operation point is outside the unstable flow regime. But such an operational change may have the disadvantage of decreasing the output
10   flow to a level substantially lower than the capacity of the pipeline. Severe variations of pressure along different positions of the pipeline may also occur.

Procedures are rule-based calculations applied by the operator. These are often used during pipeline, riser or
15   well flow line startup. Such rule-based calculations may some extent decrease the magnitude of slugging and reduce the variations in pressure in the flow-line. But a problem is that the approach with rule-based calculations may only decrease the magnitude of slugging at certain operating
20   conditions. And the operating conditions may vary widely.

Prior art control methods include:

Feed-forward control to a separation unit process control system. In this approach the slug is coped with inside the separation unit. US 5,256,171 shows a method, which
25   utilizes process measurements inside the separation unit.

US 5,544,672 shows slug choking, which utilizes measurements downstream of the point of slug generation and chokes the pipeline control valve in the presence of a slug.

30   By conventional control methods one usually refers to feed-forward or slug choking. Conventional control methods may reduce the negative effects of slugging and flow variations

in a pipeline. A remaining problem by applying conventional control methods is to stabilize the multiphase flow in a complete flow line and not only reducing the effect of slugging at a single point of the flow line, typically the
5   outlet of the flow line. Another problem with conventional control methods is that they have not proven to be efficient enough when it comes to stabilize multiphase flow and particularly not in flow-lines comprising remote well-head platforms and subsea wells.

10   In the light of the problems mentioned above, the inventor has found that there is a need for a more efficient method for stabilizing multiphase flow caused by slugging.

SUMMARY OF THE INVENTION
An object of the invention is to provide a method, which
15   stabilize a multiphase flow, in a flow line, where flow instability is caused by at least one slug. Measurement of pressure or temperature is taken upstream the point where the main part of the slug is generated. The pressure measurement, or an estimated pressure calculated from the
20   temperature measurement, is supplied to a dynamic feedback controller which dynamic feedback controller calculates an output controlling at least one control valve, wherein the multiphase flow is stabilized throughout the complete flow line.

25   By a flow line is meant a line conducting transport of a multiphase mixture of oil, gas and water such as, a pipeline, riser or a well flow line.

Another object of the invention is to provide a computer program product, which performs the steps of the above-
30   mentioned method including applying a control program or control law.

By a control valve is meant a valve or a choke equipped with an actuator suitable for automatic control, such as an

electric motor as actuator with positioning control, a
stepping motor or a pneumatic actuator.

Another advantage of the present invention is that it
improves the stability of operating conditions in
5   production facilities for oil and/or gas. In particular the
invention significantly reduce the disturbances in feed to
the separation process by avoiding flow variation at the
outlet of the multiphase flowline that connect wells and
remote installation of the processing unit.

10   Another advantage of the invention, compared with a
conventional control method, is that the invention reduces
the pressure fluctuations at the flow line inlet. This
stabilizes the multiphase flow line, which makes it
possible not only to reduce the effects of slugging, as in
15   the case of conventional methods, but also to entirely
avoid slugging.

An advantage of the invention, compared with a conventional
control method, is that it stabilizes the multiphase flow
trough out the complete flow line. This also means that by
20   applying the invention the production rate, for instance at
a production platform, may be increased.

An advantage of the invention is that, compared with
conventional methods, it reduces the number of occurrences
and formations of slugs in a flow line. In this way the
25   invention enables energy to be used in a more efficient way
in the flow line in order to transport a multiphase mixture
of oil, gas and water. This in contrast of letting energy
out of the system in the form of blowouts as slugs leaves
the outlet of flow line, such as the outlet of a riser.

30   Another advantage of the invention, compared with
conventional methods using design changes, is that it does
not require new process equipment to be installed. Hence,
substantial capital investment is avoided. It is however

assumed that there is at least one available pressure or
temperature measurement along the flow line upstream the
point where the main part of the slug is generated. It is
also assumed there is at least one control valve in the

5   flow line.

It is an aim of the invention to supply a method, which
applies a dynamic feedback controller, which is a
multivariable input, single output controller, acting upon
periodic variations in measured variables.

10   It is a further aim of the invention to stabilize the
multiphase flow at any point of the flow line.

The above mentioned objects and aims are met by the
invention as defined by the accompanying patent claims 1-
16. In particular, a method for stabilizing a multiphase

15   flow through a flow line where instability of the
multiphase flow is caused by at least one slug is defined
by independent claim 1, and a computer program product is
defined by independent claim 17, and use of a computer
program product according to independent claim 19.

20   These and other advantages with the present invention and
aspects of it will become apparent from the detailed
description and from the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS
Figure 1 is a schematic overview of the topology of a flow

25   line, such as a pipeline, between a wellhead platform and a
production platform.

Figure 2a shows a schematic overview of an implemented
control calculation for active feedback control of slug
flow through a flow line. Further the figure shows that the

30   measurement of a pressure variable is positioned upstream
the position where the main part of a slug is generated. A
method according to the invention use the active feedback

controller to close/open a control valve, which control
valve is also shown in the figure.

Figure 2b shows a schematic overview of an alternative
embodiment of an implemented control calculation for active
5   feedback control of slug flow through a flow line.

Figure 3 shows the different blocks involved in an
implemented control calculation for active feedback control
of a flow line which control calculation is used by a
method according to the invention.

10   Figure 4 shows the different controller modes and the
transitions between them in an implemented control
calculation for active feedback control in order to
stabilize a multiphase flow in occurrence of slugs through
a flow line.

15   Figure 5 shows multiphase flow simulations of terrain
induced slug flow. The upper part of the figure shows a
flow inlet, such as a pipeline inlet, PT1 and outlet PT2
pressure and the lower part shows flow line outlet flow
rates. This figure shows that the multiphase flow is
20   unstable in the case of a slugging and prior art technique
is used.

Figure 6 shows multiphase flow simulations of terrain
induced slug flow. Each line represents the pipeline
profile plot of liquid volume fraction. The sampling rate
25   is one minute. This figure shows that the multiphase flow
is unstable in the case of a slugging and prior art
technique is used.

Figure 7 shows how an active feedback controller based on
the invention stabilizes a terrain-induced slug. The upper
30   part of the figure shows pipeline inlet PT1 and outlet PT2
pressure, the middle part show pipeline outlet flow rates

and the lower part shows the controller output U1 to the control valve 2.

Figure 8 shows the effect of on flow stability by applying an active feedback controller according to the invention on
5   the same flow line and same case as in Figure 7. There are 240 plots in the figure, which represents the liquid volume fraction but they appear as one. Figure 8 should be compared with the Figure 6 where no dynamic feedback control is used and slugging occurs.

10 Figure 9 shows a dynamic feedback control startup and operation of a flow line, such as a pipeline. The upper part of the figure shows pipeline inlet PT1 and outlet PT2 pressures, together with 12h moving average in the same variables. The figure is based on the results and
15 measurements made when applying the invention at an off-shore oil production facility.

Figure 10 shows a dynamic feedback control startup and operation of a flow line, such as a pipeline. Upper part shows pipeline inlet gas flow rate. Lower part shows
20 pipeline inlet liquid flow rate. Both 30 minute and 8 hour moving average are plotted.

Figure 11 shows the four stages in a severe slug cycle.

Figure 12 shows pipeline profile for deep-water riser example.

25 Figure 13 shows a severe riser induced slug flow cycle in a deep-water riser. This figure shows that the multiphase flow is unstable in the case of a slugging and prior art technique is used.

Figure 14 shows the effect of choking of severe riser
30 induced slug flow. This figure shows that the multiphase

flow is unstable in the case of a slugging and prior art technique is used.

Figure 15 shows the effect of choking of severe riser induced slug flow. This figure shows that the multiphase

5   flow is unstable in the case of a slugging and prior art technique is used. Chocking the control valve has a mitigating effect on slugging, but the flow is not stabilized.

Figure 16 shows pipeline profile plots of liquid volume

10   fraction through a severe riser induced slug flow cycle.

Figure 17 shows the effect of choking of severe riser induced slug flow.

Figure 18 (upper part) shows pipeline profile plots of liquid volume fraction through a severe riser induced slug

15   flow cycle. The figure (lower part) also shows the height of the flow line.

Figure 19 shows how a multiphase flow during startup, operation and controller stop of a deep-water riser. This as a method based on the invention is applied using a

20   dynamic feedback controller.

Figure 20 (upper part) shows pipeline profile plots of liquid volume fraction with an active feedback controller according to the invention in operation. The figure (lower part) also shows the height of the flow line.

25   Figure 21 shows a dynamic feedback controller startup, operation and controller stop of a deep-water riser.

Figure 22 shows pipeline profile plots of liquid volume fraction with a dynamic feedback controller according to the invention in operation (upper part of figure).

30

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 shows a schematic topologic overview of a flowline
control system 3 based on the invention. The figure also
shows that as an example the flowline 8a could be a

5   pipeline between a wellhead platform 1 and a production
platform 7. Several flow lines 4 may operate in parallel.
In the example where the flowline 8a connects to a
production platform 7 the platform comprises a compressor 6
and a first 5a and second stage 5b separator.

10   A method according to the invention for stabilizing a
multiphase flow in a flow line 8a, where instability of the
multiphase flow is caused by at least one slug 8b, or
slugging, comprises the following steps:

- measuring continuously one pressure variable 26 upstream
15   the point where the main part of the slug 8b is generated,

- supplying at least the pressure variable mentioned above
to a dynamic feedback controller,

- calculating continuously an output 11 of the dynamic
feedback controller 9,

20   - controlling the opening of a control valve 2 at said flow
line 8a, wherein the multiphase flow is stabilized through
the flow line 8a.

Figure 2a shows an overview of a dynamic feedback
controller 9 for stabilization of a multiphase flow through

25   a flowline such as a pipeline and/or a riser 8a. As an
example the flowline connects a wellhead platform 1 and a
production platform 7. The multiphase flow comprises liquid
and gas. Such an embodiment is not limited to pipelines
from wellhead platforms to production platforms, but is

30   applicable to any flow line such as from a subsea manifold.
Figure 2a also shows a schematic image of generation of a
slug 8b.

The dynamic feedback controller 9 is implemented in such a
way that it stabilizes the flow through the flowline 8a, as

indicated in figure 2a, by use of a control valve 2, which is automatically controlled.

A method according to the invention uses a pressure variable PT1 26 upstream of any liquid plug. The variable
5   PT1 is a pressure measurement or as an alternative a temperature measurement can be used from which the pressure is calculated. Yet, another alternative to is to calculate the pressure variable on other measurements. As an example one measurement at the flow line inlet and a measurement
10   upstream or down stream the control valve is used as input to calculate/estimate the pressure variable.

- o Pressure measurements PT1 26 at inlet 12, or at some point upstream of the control valve 2, measuring pressure variations upstream of the liquid plug 8b.

15   Figure 2b shows an overview of an alternative dynamic feedback controller 9 for stabilization of a multiphase flow through a pipeline or a riser 8a between a wellhead platform 1 and a production platform 7. Each of the indicated measured variables improves the performance of an
20   embodiment of the invention:

- o Pressure measurements PT2 27 at the outlet 13, upstream of control valve 2.

- o Pressure difference across the pipeline 8a, or a part of the pipeline, based on the two measurements PT1 26
25   and PT2 27.

- o Flow measurements FT1 28 at the inlet 12, or at some point upstream of the outlet 13, measuring flow variations upstream of the liquid plug 8b.

- o Flow measurements FT2 29 at the outlet 13, upstream of
30   the control valve 2.

Measurements can be made topside as well as subsea.

Enhanced control can be achieved by including additional
measurements (flow, density and temperature). In case flow
measurements are included, estimates of flow conditions in
5   the pipeline/riser/well flow line 8a will be improved.

A distinct difference between the dynamic feedback control
disclosed by the invention compared with traditional
control methods is the use of measurements upstream of the
position of the slug formation. Whereas the other methods
10   have a mitigating effect, the dynamic feedback control
improves the stability of the pipeline flow and in a much
more efficient way reduces the occurrence of slugs. That is
achieved at a higher mean flowrate than what is possible
with traditional control methods. Further the dynamic
15   feedback controller according to the invention reduces the
variation of flow line inlet pressure.

In case of any kind of failure, output 11 will go to a pre-
defined value.

The dynamic feedback controller 9 has proved to stabilize
20   the flow both by simulation and also by field tests. The
dynamic feedback controller 9 allows stabilization of
pipeline variables (pressure, temperature, holdup, and
flow), at any point in the pipeline/riser 8a. This means
that the controller 9 is not limited to stabilization only
25   at the outlet 13 of the flow line.

In an alternative embodiment of the invention, a
calculation for slug detection is used together with
dynamic feedback controller. In addition to utilizing the
same measurements as the dynamic feedback controller 9, the
30   slug detection calculation also uses the pressure upstream
of the control valve as input. The output from the slug
detection calculation is typically used for information
purposes, notifying personnel about an upcoming slug 20-30

minutes in advance. The information is for instance
displayed on computer screens in the control room. In one
embodiment of the invention the slug detection calculation
is used in order to stabilize the multiphase flow even
5   further.

The dynamic feedback controller

The dynamic feedback controller 9 is preferably a
multivariable input, single output controller. The dynamic
feedback controller is preferably described in a state-
10   space form and implemented in a control program for a
control means. A control means comprises at least one out
of an industrial controller, a programmable logic computer
(PLC), an industrial purpose computer, a general-purpose
computer or a purpose built device for stabilization of
15   multiphase flow. A particularly useful and efficient
implementation is achieved by using structured text
according to the IEC 1131 program language standard. This
and other ways of implementation a control program, based
on a state-space form is well known to a person skilled in
20   the art.

Figure 3 shows the dynamic feedback controller in more
detail. The controller consists of the following blocks:

      o 14:   Feedback stabilization ensures that the pipeline
              flow is stabilized.

25   o 15:   Slug choking throttles the control valve in the
              presence of a slug (pressure rise upstream of the
              pipeline choke 2).

      o 16-19:   Filters for input signals

      o 20:   Manual/auto switch

30   o 21-25:   Max and min function blocks

The input signals to the dynamic feedback controller are:

- o PT1: Pressure 26 at the pipeline inlet, 12.

- o Set point PT1: desired/nominal value (SP PT1) 10 for pressure at pipeline inlet, 12. The operator typically enters the nominal value of the set point PT1. As an alternative a computer program may calculate the set point PT1.

- o PT2: Pipeline pressure 27 upstream of the choke, 13.

- o Set point PT2: nominal value (SP PT2) 28 for pipeline pressure upstream of the choke, 13.

- o Output High Limit (OHL): upper limit 33 for the controller output U1 and U2.

- o Output Low Limit (OLL): lower limit 34 for the controller outputs U1 and U2.

- o Manual Output Value (MOV): output value 35 from the controller when it is in manual mode.

- o Mode: operator defined controller mode 36.

The output signals from the dynamic feedback controller shown in Figure 3 include:

- o Filtered PT1, filtered pressure measurement one 37.

- o Filtered PT2, filtered pressure measurement two 38.

- o U1: Controller output 39 to be wired to the flow line, such as a pipeline, control valve (2).

- o U2: Controller output 40 based on measurement PT1 26.

   o U3:   Controller output 41 based on measurement PT2 27.

Additional output signals from the controller (not shown in Figure 3) include:

   o Filtered set-point for PT1

   o Filtered nominal value for PT2

   o Controller state

   o Controller 'I am alive signal'

Alarm signals from the controller (not shown Figure 3) include:

   o High output limit alarm

   o Low output limit alarm

   o Read fail alarm

The block diagram in Figure 3 shows the following interconnections:

1. The feedback U2 40 and U3 41 from the two measurements PT1 and PT2 are calculated independently.

2. The output U2 40 from Feedback stabilization 14 is restricted to be within the upper 21 and lower 22 output limits.

3. The output U3 41 from the slug choking calculation 15 is restricted to be below zero 23.

4. The sum of U2 40 and U3 41 is one of the two inputs to the controller mode switch 20. Depending on the operator-defined controller mode, the output from the

switch is either the sum of U2 and U3 or the operator-defined Manual Output Value 35.

5. The output U1 from the controller mode switch 20 is
    then restricted by the maximum and minimum function
5   blocks to be within the upper 33 and lower 34 output
    limits.

The next paragraphs describe the feedback stabilization 14,
slug choking 15, filters 16-19 and the combination of the
blocks into the complete dynamic feedback controller. The
10 description of each part is on three levels. Level one is
an overview where the purpose of the block is clarified.
Level two is a comprehensive mathematical description of
the block, and level three discloses a detailed description
of the implementation.

15
Feedback stabilization
The inventor has found that a calculation of the feedback
stabilization 14 is beneficial in order to stabilize
terrain and riser induced slug flow.

20 Level one. The purpose of the calculation of the feedback
stabilization is to achieve control of the pipeline inlet
pressure, which is the main contributor to the driving
force of the flow through the pipeline or riser. The
feedback stabilization 14 acts upon slow periodic
25 variations in the pressure measurement PT1 by including
control action at low frequency, e.g. integral action. The
feedback stabilization 14 may have built-in logic to
prevent anti-windup. The anti-windup scheme is implemented
by preserving the old control output in the state of the
30 controller, and by this only a smaller set (subspace) of
these states are limited.

Level two. An example of how to calculate feedback
stabilization 14 is described by the following difference
equation:

$$\Delta u_{2,k} = K\left(\Delta e_{f,k} + T_s / T_1 e_{f,k} + T_2 / T \Delta \Delta e_{f,k}\right)$$

where T_s is the sampling time, K, T_1 and T_2 are tuning
5   parameters, the operator Δ means $\Delta m_k = m_k - m_{k-1}$ and $e_{f,k}$ is
filtered error (set-point minus measurement). The filter to
obtain the filtered control error is a first-order filter
of the type described below. The feedback stabilization
controller is implemented based on a state-space form and
10   the state in the controller has been given special ordering
so that integral windup is easily implemented.

Level three. In an embodiment of the invention the
calculation of the feedback stabilization 14, is
implemented based on the state-space realization:

$$
\begin{bmatrix} x_{FS,k+1}(1) \\ x_{FS,k+1}(2) \\ x_{FS,k+1}(3) \\ x_{FS,k+1}(4) \end{bmatrix}
=
\underbrace{\begin{bmatrix}
1 & K_p(1+T_s/T_i+T_d/T_s) & -K_p(1+2T_d/T_s) & K_pT_d/T_s \\
0 & e^{(-T_s/T_f)} & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}}_{\Phi_{FS}}
\underbrace{\begin{bmatrix} x_{FS,k}(1) \\ x_{FS,k}(2) \\ x_{FS,k}(3) \\ x_{FS,k}(4) \end{bmatrix}}_{x_{FS,k}}
+
\underbrace{\begin{bmatrix}
0 & 0 \\
-(1-e^{(-T_s/T_f)}) & 1-e^{(-T_s/T_f)} \\
0 & 0 \\
0 & 0
\end{bmatrix}}_{\Gamma_{FS}}
\begin{bmatrix} y_k(1) \\ y_k(3) \end{bmatrix}
$$

$$
u_{k+1}(2) = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}}_{C_{FS}}
\underbrace{\begin{bmatrix} x_{FS,k+1}(1) \\ x_{FS,k+1}(2) \\ x_{FS,k+1}(3) \\ x_{FS,k+1}(4) \end{bmatrix}}_{x_{FS,k+1}}
$$

15

The first element in the state vector $x_{FS,k}(1)$ contains the
previous feedback stabilization controller output. The
states $x_{FS,k}(2)$ to $x_{FS,k}(4)$ contain the current and the two
previous filtered control errors. The state of the feedback
20   stabilization x_{FS} is updated when the controller is running
into the high and low output limits. That is, the non-
linear saturation logic functions 21 and 22 interfere with
the state of the feedback stabilization calculation. The
same kind of interference also appears when the controller
25   is in the manual and the starting mode.

Slug choking

Level one. The purpose of the slug choking calculation 15
is to throttle the control valve 2 of the flowline in the
presence of a slug, i.e. when the slug approaches the
5   outlet of the pipeline or riser. The pressure measurement
PT2, upstream of the flowline control valve 2, increases
rapidly whenever a liquid plug approaches the point of
measurement PT1. The slug-choking calculation 15 therefore
uses PT2 as input and acts upon pressure increase in this
10   measurement by choking the control valve 2. By choking the
controller is able to reduce the velocity of the liquid
plug. Experience from simulation and field-tests shows that
moderate use of choking in the presence of the slug has a
stabilizing effect.

15   Level two. On continuous form the slug choking feedback
controller 15 has the following form:

$$K(s) = k\frac{s}{(\tau_1 s + 1)(\tau_2 s + 1)}, \qquad u_3(s) = K(s)e_2(s)$$

where $K(s)$ is the Laplace transform of the slug chocking
controller, u_3 is the controller output (the control valve
20   opening) and e_2 is the filtered nominal value for PT2 minus
PT2. Tuning parameters are the frequencies $f_1 = 1/\tau_1$ and
$f_2 = 1/\tau_2$, and the controller gain k.

21

Level three. With sampling time T_s and Zero Order Hold (ZOH) a discrete time state-space description of the controller $K(s)$ is:

$$
\underbrace{\begin{bmatrix} x_{sc,k+1}(1) \\ x_{sc,k+1}(2) \end{bmatrix}}_{x_{sc,k+1}} = \underbrace{\begin{bmatrix} e^{-T_s/\tau_1} & 0 \\ 0 & e^{-T_s/\tau_2} \end{bmatrix}}_{\Phi_{sc}} \underbrace{\begin{bmatrix} x_{sc,k}(1) \\ x_{sc,k}(2) \end{bmatrix}}_{x_{sc,k}} + \underbrace{\begin{bmatrix} k_p\left(1-e^{-T_s/\tau_1}\right) \\ k_p\left(1-e^{-T_s/\tau_2}\right) \end{bmatrix}}_{\Gamma_{sc}} \left(\underbrace{y_k(2)-y_k(4)}_{e_k(2)} \right)
$$

$$
u_{k+1}(3) = \underbrace{\begin{bmatrix} \dfrac{1}{\tau_2-\tau_1} & \dfrac{-1}{\tau_2-\tau_1} \end{bmatrix}}_{C_{sc}} \underbrace{\begin{bmatrix} x_{sc,k+1}(1) \\ x_{sc,k+1}(2) \end{bmatrix}}_{x_{sc,k+1}}
$$

5

Filters

Level 1. The purpose of the filters 16 - 19 and the filter inside the feedback stabilization calculation 14, is to filter the error signal to ensure smooth changes in

10   operation point and filtering of high frequency noise.

Level 2. The filters are all first-order low pass filters with unity steady-state gain. The common form of these filters is:

$$
F(s) = \frac{1}{T_f s + 1}, \quad y_f(s) = F(s)y(s)
$$

15   Level 3. With sampling time T_s and ZOH, a discrete time state-space description of the continuous filter $F(s)$ is:

$$
x_{f,k+1} = \underbrace{e^{-T_s/T_f}}_{\Phi_f} x_{f,k} + \underbrace{(1-e^{-T_s/T_f})}_{\Gamma_f} y_k, \quad y_{f,k+1} = \underbrace{1}_{C_f} x_{f,k+1}
$$

The full state-space dynamic feedback controller

Level 1. The individual dynamic parts of a dynamic feedback

20   controller are described above. These parts are put

together into one state-space description of the dynamic feedback controller.

Level 3. In an embodiment of the invention a state-space an example of representation of the dynamic feedback

5 controller 9 is:

$$x_{k+1} = \Phi x_k + \Gamma y_k, \ u_{k+1} = C x_{k+1} + D y_k,$$

where

x_k is the state-space vector of the controller

y_k is the input vector to the controller (measurements

10 and set points/nominal values etc.)

u_k is the output vector from the controller

The elements in the input vector y_k are:

$y_k(1)$ pipeline inlet pressure 26, PT1

$y_k(2)$ pressure upstream the control valve 2, PT2

15 $y_k(3)$ set-point 10 for pipeline inlet pressure, PT1

$y_k(4)$ nominal value for pressure upstream of the
          control valve 2, PT2

The elements in the state vector x_k are:

$x_k(1)$ previous control value, i.e. $u_{k-1}(2)$

20 $x_k(2)$ filtered control error at time k, i.e. $e_{f,k}$

$x_k(3)$ filtered control error at time k-1, i.e. $e_{f,k-1}$

$x_k(4)$ filtered control error at time k-2, i.e. $e_{f,k-2}$

$x_k(5)$ Filtered PT1

$x_k(6)$ Filtered PT2

$x_k(7)$ Filtered set-point to PT1

$x_k(8)$ Filtered nominal value for PT2

5        $x_k(9)$ State one in the slug choking calculation

$x_k(10)$ State two in the slug choking calculation

$x_k(11)$ Controller state

0 Manual

1 Starting

10   2 Auto

The elements in the output vector u_k are:

$u_k(1)$ Output 39 from the dynamic feedback controller

$u_k(2)$ Output 40 from the feedback stabilization 14

$u_k(3)$ Output 41 from the slug choking 15

15       $u_k(4)$ Filtered pressure measurement 37 PT1

$u_k(5)$ Filtered pressure measurement 38 PT2

$u_k(6)$ Filtered set-point 16 for pressure measurement
            PT1

$u_k(7)$ Filtered nominal value 18 for pressure
20   measurement PT2

The matrices Φ, Γ, C, D are:

$$\Phi = \begin{bmatrix} \Phi_{FS} & 0_{4\times4} & 0_{4\times2} & 0_{4\times1} \\ 0_{4\times4} & \Phi_{filter} & 0_{4\times2} & 0_{4\times1} \\ 0_{2\times4} & 0_{2\times4} & \Phi_{sc} & 0_{2\times1} \\ 0 & 0 & 0_{1\times2} & 1 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} \Gamma_{FS} \\ \Gamma_{filter} \\ \Gamma_{sc} \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0_{1\times4} & 0_{1\times4} & 0_{1\times2} & 0 \\ C_{FS} & 0_{1\times4} & 0_{1\times2} & 0 \\ 0_{1\times4} & 0_{1\times4} & C_{ss} & 0 \\ 0_{4\times4} & I_{4\times4} & 0_{4\times2} & 0_{4\times1} \end{bmatrix}, \quad D = 0_{7\times4}$$

$$\Phi_{filter} = \begin{bmatrix} e^{-T_s/T_1} & 0 & 0 & 0 \\ 0 & e^{-T_s/T_2} & 0 & 0 \\ 0 & 0 & e^{-T_s/T_3} & 0 \\ 0 & 0 & 0 & e^{-T_s/T_4} \end{bmatrix}, \quad \Gamma_{filter} = \begin{bmatrix} 1-e^{-T_s/T_1} & 0 & 0 & 0 \\ 0 & 1-e^{-T_s/T_2} & 0 & 0 \\ 0 & 0 & 1-e^{-T_s/T_3} & 0 \\ 0 & 0 & 0 & 1-e^{-T_s/T_4} \end{bmatrix},$$

where $0_{m\times n}$ is a $m\times n$ matrix with zeros, T1 to T4 are filter time constants and Ts is the sampling interval.

5 **Fixed controller output and state update**
Whenever the controller output is fixed, due to

    1. Manual mode

    2. Startup mode

    3. Low or high saturation

10 the controller state is updated so that it goes smoothly out of the fixed output or the saturation. This is achieved by updating the previous controller output in the feedback stabilization calculation.

15 **Dynamic feedback controller modes and transitions**
Figure 4 shows three different modes. The description below regarding controller modes may be of use when implementing the controller. The three modes are:

1. Manual 42: The controller is running, but the output
   from the controller to the control valve (2) is kept
   constant.

2. Startup 43: The controller is running but does not
   update the output to the control valve (2). It tests
   for certain process and controller conditions to
   appear in order to initiate a transition from starting
   to auto.

3. Auto 44: The controller is running and updates the
   controller output to the control valve (2).

The operator initiates the transition 45 from Manual 42 to
Startup 43 mode by setting the controller mode input 36 to
Auto.

The transition 46 from Startup 43 to Auto 44 depends of the
process measurements and the calculated output from the
controller. The controller will only go from startup to
auto if:

1. The controller input mode 36 is in Auto and

2. process measurement PT1 26 is decreasing and

3. the calculated output U1 39 is decreasing.

The Startup mode 43 is included to ensure the best possible
condition for flow stabilization.

The transitions from Startup 43 to Manual 42 and from Auto
44 to Manual 42 are initiated by changing the mode input 36
from Auto to Manual.

One alternative when implementing the controller, compared
with the description of transitions between modes as

described above, is to implement the controller to go
directly from Manual to Auto mode.

Controller startup

Depending on the characteristic of an individual flowline
5   the controller startup should be adjusted to handle
specifications and limitations of that flowline. Below is
one example of a controller startup. According to the above
section "Dynamic feedback controller modes and
transitions", as an operator changes the operator-defined
10   mode 36 from Manual (zero) to Auto (one), the controller
first goes into a Startup mode 43. In the Startup mode, the
controller updates all of its internal states, however the
controller output to the control valve 2 remains constant.
When certain process and controller conditions are
15   fulfilled the controller starts to update the control valve
2. The reason for the special startup sequence is that it
is not possible to stabilize the pipeline flow from an
arbitrary pipeline state. As the controller goes from
Manual mode to Startup, it initially decreases the opening
20   of the control valve.

Changes in operating point

It is advantageous to use filters for changes of the
operating point. An operator request to change the
25   operating point, by a change of the set-point/nominal
values of the pressure, is filtered by the two filters 16
and 18. The filters are included to ensure smooth
transition from one operating point to another.

Controller operation

30   The controller set-point 10 variation depends on the mean
(typically 2 to 8 hours moving average) pipeline input flow
measurement FT1 and/or the mean (typically 1 to 4 hours
moving average) control valve opening 2.

The feedback stabilization calculation 14 adjusts the opening of the control valve 2 to achieve the desired pressure (the set-point 10) at the pipe inlet PT1.

The slug choking calculation 15 closes the control valve 2
5   whenever the pressure measurement PT2 upstream of the control valve 2 increases rapidly. This control action returns to zero over some time (typically a few minutes) whenever PT2 stops increasing or decreasing. The control action in the slug choking 15 and the feedback
10   stabilization 14 act on the control valve at different frequencies by proper adjustment of the tuning factors:

T_f in the feedback stabilization calculation.

τ_1 and τ_2 in the slug choking calculation.

The feedback stabilization calculation 14 acts upon slow to
15   medium periodic variations (typically in the range of 5 minutes to several hours) in the measurement PT1 26 by including control action of low frequency, e.g. integral action. The feedback stabilization 14 has built-in logic to prevent anti-windup. The anti-windup scheme is implemented
20   by giving the controller states a specific ordering, and by this only a smaller set (subspace) of these states are limited.

Pipeline simulations
Figure 11 is included in order to facilitate a better
25   understanding of what a typical slug cycle in a flow line looks like. The details of Figure 11 are described in the section below.

Simulations are made by use of the simulation environment OLGA. The models used for simulations are based on fluid
30   mechanics well known to a person skilled in the art. The upper part of Figure 5 shows the result of multiphase flow simulations of terrain-induced slug flow. The position of

the control valve 2 is constant, in other words there is no
feedback control applied to the simulations. The lower part
of Figure 5 shows that the liquid flow rate 52 at the
pipeline output is zero for a period of about 2 hours.

5   During this time, the pressure upstream of the liquid plug
builds up, Figure 11-I. When the inlet pressure 51 exceeds
the hydrostatic pressure of the liquid column in the riser,
the liquid accelerates and the outlet pressure 50 rises at
the pipe outlet, Figure 11-II and Figure 11-III. The liquid

10 is transported to the outlet of the pipe and the pressure
decreases as the gas and liquid escape through the
pipeline, Figure 11-IV. The process then repeats itself.
The variation in gas flow 53 and liquid flow 52 rate
corresponding to the slug flow is shown in the lower part

15 of Figure 5.

Figure 6 shows the pipeline profile plot of the liquid
volume fraction 54, sampled each minute during one slug
cycle. Figure 6 corresponds to one of the slug cycles in
Figure 5. It is not what happens at different time points

20 that is important here, but what happens at different
positions in the pipeline during the cycle. The position in
the pipeline is indicated on the x-axis and the
corresponding liquid volume fraction is indicated on the y-
axis. Positions where the difference between the maximum

25 and the minimum liquid volume fractions are large have the
potential to initiate terrain-induced slug flow.

Figure 7 shows the simulated performance of the dynamic
feedback controller according to the invention at hand.
During the first eight hours the controller is in manual

30 mode and the multiphase flow is unstable as indicated by
the characteristic pressure swings in the pipeline inlet
pressure 56 and outlet pressure 57. The controller starts
at t=28h and spends the next 5 to 7 hours stabilizing the
pipeline. The slugging behavior disappears. From figure 7

35 it may be concluded that the controller has stabilized the
multiphase flow and holds the valve opening 58 at a

constant output value at t=38h. However, that the valve
opening is held at a constant value is not entirely true.
As the controller output 58 is magnified, it becomes clear
that the controller constantly makes small movements in the
5   output around its mean value. Those movements controlled by
the dynamic feedback controller are necessary to keep the
multiphase flow stable. Further in Figure 7, the controller
is set to manual at t=45h, with its output equal to the
mean value of the control valve opening over the previous 3
10   hours. It is seen from Figure 7 that with the controller
set back to manual the multiphase flow once again becomes
unstable. However, the transition into an unstable
multiphase flow is slow. Still, Figure 7 shows that with
the dynamic feedback controller turned off the slug flow
15   once again builds up. This despite of that the output of
the controller, which sets the control valve opening 58,
seemed to be at an optimum level. To stabilize the
multiphase flow, at the indicated gas and liquid flow
rates, the dynamic feedback controller according to the
20   invention is needed.

From Figure 7 it seems reasonable to assume that the
complete flowline is stabilized as the dynamic feedback
controller is started. This since the input pressure 56 and
at the output pressure 57 are stabilized. However, due to
25   the length of the pipeline, it could be claimed that
internal instability might occur in it.

Figure 8 shows the profile plots of the resulting liquid
volume fraction for the case same case as in Figure 7. The
profile plots of Figure 8 corresponds to the time period
30   from t=41 to 45h, i.e., which is part of the period in
figure 7 where the multiphase flow is stabilized. The
profile plots of the liquid volume fraction are sampled at
60-second intervals. The number of profile plots of the
liquid volume fraction are 240, all lying on top of each
35   other. In this context, stabilization of the multiphase
flow is defined by the liquid volume fraction at any point

of the flow line showing less than 5% variation around its mean value. The mean value is calculated based on measurements taken during a time interval, where a time interval corresponds to the time of at least one complete
5   slug cycle in the flow line without applying control. Indeed, figure 8 shows that the multiphase flow in the pipeline is stabilized according to this definition, and not only in one single point but also through the complete flow line. Figure 8 should be compared with Figure 6 where
10   no dynamic feedback control is used. In contrast to Figure 8, Figure 6 shows large variations in the liquid volume fraction. When comparing the two figures it is clear that in this case the dynamic feedback controller clearly stabilizes the multiphase flow throughout the flowline.

15   **Riser simulations**
This section presents results from a deep-water pipeline-riser system, which is simulated by use of the simulation environment OLGA. Figure 12 shows the pipeline geometry. The total length is approximately 6500 m with a 5000 m
20   flow-line on the seabed and a 1500 m long riser. The inclination from the wellhead to the riser base is 1° downward slope. The sea depth at riser base is 1320 m. A source is located at the inlet of the pipeline. The boundary conditions at the inlet are closed and at the
25   outlet the pressure is set equal to 15 Bar. A control valve is located at the top of the riser. This control valve will be used to control the multiphase flow in the riser.

Two different inlet condition cases are simulated. The first case is at the start of the production profile. The
30   input flow rate is in case one set to 6000 Sm^3/d and the gas fraction is read from the PVT table with the pressure and temperature in the inflow section (the first section in the pipeline) as input to the table. This means that the gas fraction and thereby also the Gas Oil Ratio GOR may
35   vary to some degree. The GOR varies around 125 Sm^3/Sm^3. In the second case the GOR is set equal to 250 Sm^3/Sm^3 and the

flow rate is set equal to 2000 Sm^3/d. In both case one and
case two the water cut is zero, hence two-phase simulations
are considered.

Case one - using a traditional control method

5   Figure 13 to Figure 16 show simulations of riser-induced
slug flow (severe slugging) with an input flow rate of 6000
Sm^3/d with GOR around 125 Sm^3/Sm^3. The simulation is applied
on the flowline with the profile according to Figure 12.

Figure 13 shows a severe riser induced slug cycle. It is
10   worth to note the following:

1. The substantial variations in the pipeline inlet
   pressure 75 and outlet pressure 76.

2. The outlet oil flow rate 77 is nonzero for a large
   portion of the time as opposed to terrain-induced slug
15   flow. The reason is that the liquid plug extends far
   into the nearly horizontal pipeline before the riser
   and it takes some time to produce the liquid in the
   pipeline, cf. Figure 11-II.

3. The simulations show a considerable amount of
20   flashing, which gives rise to a gas-lift effect. The
   gas-lift effect gives a rapid increase in the outlet
   oil flow rate 77 observed as the first peak in the
   slug flow cycle. The latter peak in the outlet oil
   flow rate 77 is related to the blow-out of the riser,
25   i.e., emptying the riser, cf. Figure 11-III.

Figures 14 and 15 show the effect of a stepwise closing of
the control valve from 100% to 20%. It should be noted
that:

1. In order to get out of the region with unstable riser
30   induced slug flow and to some level stabilize the
   outlet flow rate 82 and the outlet flow rate 87, it is

seen that the control valve 2, according to the
plotted control valve position 83 and 88, needs to be
closed more than 20%.

2. In order to reduce the peak in the outlet oil flow
5   rate significantly by constant choking, the valve
       needs to be closed more than 40%.

Figure 15 shows that the control valve needs to be closed
as much as 14% to achieve stable out let flow conditions by
choking a pipeline inlet pressure of approximately 135 bar.

10 Figure 16 shows profile plots of liquid volume fraction
through one slug flow cycle. The shaded area corresponds to
900 lines laid on top of each other. There are 10 seconds
between each line. The profile plots illustrate the span in
the amount of liquid in different parts of the pipeline.
15 The following conclusions can be made:

1. The liquid plug covers a distance of 1300 m upstream
   of the riser base.

2. The liquid volume fraction in the local maximum point
   in the S-shaped riser is never larger than 50%.

20 **Case one – active dynamic feedback control**
Figures 19 and 20 show active dynamic feedback control
according to the invention, which is applied to remove the
occurrence of slugging in the multiphase flow in the
pipeline. Initially, the controller is in manual mode with
25 a control valve opening of 70%. Then, at time t=5h 100a,
the dynamic feedback controller is activated. The
controller waits for the best startup condition to occur.
This condition occurs at approximately time t=6h and at
this point the controller starts updating the output
30 (control valve). During dynamic feedback control based on
the invention the gas flow 99 and oil flow 98 is
stabilized, and from Figure 19 the controller eventually

seems to reach a constant output 100b of about 43%.
However, with a higher resolution of the plotted trend, it
becomes clear that the controller constantly makes small
movements (varying in the range of 43.1-43.2%) around its
5   mean value. The small movements in the control valve
position are necessary to keep the flow stable.

Further figure 19 shows that at time t=16 hours the
controller input mode is set back to manual mode with its
previous output (43%) as the manual output value. With the
10   controller in manual mode and with the control valve in
what seems to be the most optimum position the riser
induced slug flow again builds up. No other changes are
made. Slug flow with approximately the same control valve
opening (40%) is also predicted from the simulations
15   without control. Figure 19 shows that the invention results
in a far better stabilization of multiphase flow compared
with a prior art technique.

Figure 19 also shows that the inlet pressure with the
controller in operation is lower (103 Bar), than the case
20   without control, but with maximum opening of the choke and
at the same time stable flow (136 Bar). This is an
observation made also in other simulated cases.

Figure 19 further shows the following important points:

Less pressure drop over pipeline with active feedback
25   control than the mean pressure drop with traditional
control (this also applies to terrain induced slug flow).

Increased pressure upstream of the control valve with
active feedback control results in larger pressure drop
over the control valve. This is necessary to have an effect
30   of the movements in the control valve.

With active feedback control, liquid plugs do not occur,
only minor movements in the profile plot of liquid volume
fraction can be observed during control.

Figure 20 shows a profile plot of liquid volume fractions
during slug control. The plot shows the corresponding plot
area of 360 profile plots, 10 seconds apart. They all lie
on top of each other, implying that the pipeline indeed is
stable.

It is important to note that field tests where the
innovation is applied show the same advantages and similar
effects compared with traditional control methods as in a
simulated environment.

Case two - using a traditional control method
The deep-water riser in case two has an input flow rate of
2000 Sm^3/d and a GOR of 250 Sm^3/Sm^3. The higher GOR compared
to case one means that this case related to a lighter fluid
with more gas and less oil.

Figure 17 shows the effect of stepwise closing of the
pipeline control valve from 50% to 20%. Further figure 17
shows that:

1. The characteristics of the riser induced slug cycles
   are different from case one. From figure 17, it is
   seen that the flashing blowout is small, almost
   missing in this case. The mass transportation period
   with constant outlet flow rate is also missing.
   However, still large oscillations in the inlet and
   outlet pressure appear, which is similar to case one
   using a traditional control method.

2. The liquid flow rate is zero for a larger portion of
   the time.

The slug cycles in this case compared to case one are much
more similar to terrain induced slug flow. Figure 17 shows
that the control valve needs to be closed as much as 10% to
achieve stable flow conditions by choking with a pipeline
5   inlet pressure of approximately 65 bar. The reason for the
lower pipeline inlet pressure in this case is the larger
GOR.

Figure 18 shows profile plots (900 lines) of liquid volume
fraction through one slug flow cycle. The profile plots are
10   10 seconds apart. The profile plots illustrate the span in
the amount of liquid in different parts of the pipeline.
Figure 18 indicates that:

1) The liquid plug covers a distance of 7000 meter upstream
the riser base.

15   2) The liquid volume fraction in local maximum point in the
S-shaped riser does not exceed 70%.

By comparing Figure 18 of case two with Figure 16 of case
one, it is found that the slug does not extend to the same
extent into the horizontal part of the pipeline for case
20   two as it did for case one.

Case two - using active feedback control
Figures 21 and 22 show active feedback control of case two,
with an input flow rate of 2000 Sm^3/d and GOR 250 Sm^3/Sm^3.

Figure 21 shows that initially the controller is in manual
25   mode with a control valve opening of 100%. Then, at time
t=8h the active feedback controller is activated. The
controller waits for the best startup condition to occur.
This condition occurs at approximately time t=8.5h, at
which point the controller starts updating the output
30   (control valve). During slug control the flow is
stabilized, and again, from Figure 21 the controller seems
to reach a constant output of about 34.5%. However, if the

controller output is magnified, it becomes clear that the controller constantly makes small movements (varying in the range from 34 to 35%) around its mean value. Also in this case the small movements in the control valve position are

5 necessary to keep the flow stable. This is proved by, at time t=24 hours, setting the controller input mode at manual with its previous output (32.5%) as the manual output value. With the controller in manual and with the control valve in this position the riser induced slug flow

10 again builds up. Again, no other changes are made. Slug flow with approximately the same control valve opening (30%) is also predicted from the simulations without control, Figure 17.

It should again be noted that the inlet pressure with the

15 controller in operation is lower (41 Bar), than the case without control, but with maximum opening of the control valve (10%) and at the same time stable flow (65 Bar).

Further figure 21 shows the following effects and advantages by applying active feedback control according to

20 the invention:

1. There is less pressure drop over the pipeline with control compared with the mean pressure drop using a traditional control method.

2. The pressure increases upstream of the choke with

25   control, which results in larger pressure drop over the control valve. This is necessary to have an effect of the movements in the control valve.

3. When applying the invention on the flow line, no liquid plugs occur. Only minor movements in the

30   profile plot of liquid volume fraction can be observed during control.

Figure 22 shows a profile plot of liquid volume fractions
during slug control. The plot includes 360 profile lines,
again 10 seconds apart. They all lie on top of each other,
implying that the pipeline is stable. By comparing Figure

5   22 with Figure 20, it is found that there is much less
liquid preserved in the riser for case two than for case
one. This is also the reason for the lower inlet pressures.

If the peaks of flow rate in Figure 19 are compared with
the peaks of flow rate in figure 21, it is clear that the

10   peaks are larger for case two than for case one. We noted
in the sections presenting the simulations without control
that the peaks in the flow rates are much larger for case
two than for Case one. In addition, the fraction of time in
which the output flow rate is zero is greater for Case two.

15   However, which of these two that represents the largest and
most troublesome problem for the downstream production
plant is not clear and depends on the plant configuration.
It should be clear though that there are several benefits
with applying the invention in both cases. In the latter

20   case it is interesting to observe how much the pipeline
inlet pressure is reduced compared to pressure variations
in slug flow. This pressure reduction represents increased
production rate from the wells due to a lower backpressure.

EXAMPLE OF OPERATION IN THE FIELD, OFF-SHORE PIPELINE

25   Figure 9 shows a dynamic feedback controller during startup
and operation. The upper part of the figure shows pipeline
inlet PT1 and outlet PT2 pressure. The lower part shows
controller output U1. The controller is initially in manual
mode. After eight hours, the manual input is changed from

30   20% to 25%, and the mode is changed to auto. The controller
then goes into startup mode. Just before time 12 hours the
controller goes from startup to auto. The controller starts
to close the control valve but then opens the control valve
to lower the pipeline inlet pressure. The controller

35   stabilizes the multiphase flow in the pipeline. Figure 9

shows that as the dynamic feedback controller is active there is a significant decrease of the swings in pressure. Due to slugging in the wells connected to the platforms the controller uses the control valve to keep the pipeline
5   pressure PT1 and PT2 within bounds.

The pipeline inlet flow is shown in Figure 10. (Remark: the missing flow measurements at the beginning of the plotted trend are due to the fact that the wells were produced bypassed the test separator at the platform.) The mean
10 inlet gas flow 70 is shown in the upper part of Figure 10. The mean inlet liquid flow is shown in the lower part of Figure 10. As shown in Figure 10, the input flow rates vary. These variations represent quite large disturbances, to the dynamic feedback controller. Even though there are
15 large disturbances the dynamic feedback controller significantly reduces the slugging.

It is to be noted that the invention described above and shown in the drawings is to be regarded as a non-limiting example of the invention and that the scope of protection
20 is defined by the patent claims.

PATENT CLAIMS

1.   A method for stabilizing a multiphase flow in a flow
line (8a), where instability of the multiphase flow is
caused by at least one slug (8b), characterized by the
5   steps of
- measuring continuously one pressure variable (26)
upstream the point where the main part of the slug (8b) is
generated,
- supplying the pressure variable to a dynamic feedback
10   controller (9), wherein the pressure variable (26) upstream
of the slug (8b) is an input to the dynamic feedback
controller,
- calculating continuously an output (11) of the dynamic
feedback controller (9), and
15   - controlling a control valve (2) at said flow line (8a) by
means of the output (11) from the dynamic feedback
controller (9), wherein the multiphase flow is stabilized
through out the flow line (8a).

20   2.   A method according to claim 1, characterized in that
the dynamic feedback controller (9) is a multivariable
input, single output controller, acting upon periodic
variations in measured variables.

3.   A method according to claim 2, characterized in that
25   one of the input variables of the dynamic feedback
controller is a set-point (10) for desired pressure at the
same position in the flow line (8a) as the pressure
variable (26).

4.   A method according to claim 3, characterized in that
30   the pressure variable (26) is positioned at the flow line
inlet (12).

5.   A method according to claim 4, characterized in that
the continuous calculation of output (11, 39) of the
dynamic feedback controller is aiming at controlling the
35   control valve (2) in such way that the variation around the

set point (10) for desired pressure at the flow line inlet
(12) is minimized.

6.   A method according to claim 5, characterized in that
the pressure variable (26) is either measured by a pressure
measurement means or calculated from a temperature
measurement.

7.   A method according to claim 6, characterized in that
the control valve (2) is positioned at the outlet (13) of
the flow line (8a).

8.   A method according to claim 7 characterized in that
said pressure variable (26) is calculated based on a first
measurement made at the flow line inlet (12) and a second
measurement made upstream or downstream of the control
valve (2).

9.   A method according to claim 8, characterized in that
additional measured variables, used as input variables to
the dynamic feedback controller, comprises at least one
variable situated at the outlet (13) upstream of the
control valve (2).

10.   A method according to claim 9, characterized in that
the variable situated at the outlet (13) is a pressure
variable.

11.   A method according to claim 10, characterized in that
stabilization of the multiphase flow is enhanced by
including additional measurements of flow, pressure, and
temperature, or any combination thereof.

12.   A method according to claim 11, characterized in that
the dynamic feedback controller comprises a feedback
stabilization calculation 14 which is described by an
equation as

$$\Delta u_{2,k} = K\left(\Delta e_{f,k} + T_s/T_1 e_{f,k} + T_2/T\Delta\Delta e_{f,k}\right)$$

where T_s is the sampling time, K, T_1 and T_2 are tuning
parameters and the operator Δ means $\Delta m_k = m_k - m_{k-1}$ and $e_{f,k}$ is a
filtered control error.

5   13.   A method according to claim 12, characterized in that
the dynamic feedback controller (9) has a built-in anti-
windup prevention logic.

14. A method according to claim 13, characterized in that
the dynamic feedback controller comprises a slug choking
10   controller which is described by an equation as

$$K(s) = k\frac{s}{(\tau_1 s+1)(\tau_2 s+1)}, \qquad u_3(s) = K(s)e_2(s)$$

where $K(s)$ is the Laplace transform of the slug chocking
controller, u_3 is the controller output, e_2 is the filtered
nominal value for the pressure variable upstream the
15   control valve minus the pressure variable upstream the
control valve, the frequencies $f_1 = 1/\tau_1$ and $f_2 = 1/\tau_2$ are tuning
parameters, and k is the controller gain.

15.   A method according to any of the preceding claims,
characterized in that along with the dynamic feedback
20   controller (9), a calculation for slug detection is
applied.

16.   A method according to claim 15, characterized in that
the slug detection calculation utilizes a pressure
measurement downstream of the control valve (2).

17.   A computer program product containing software code
means loadable into the internal memory of a computer or a
process controller in a computerized control system,
characterized in that said computer program product has
5   means to make said computer or process controller carry out
the steps of a method according to claim 1.

18.   A computer program product according to claim 17,
characterized in that said computer program product has
means to make said computer or process controller carry out
10   the steps of a method according to any of the claims 2-16.

19.   Use of a computer program product according to claim
17 to stabilize a multiphase flow at a production facility
for oil and gas.

Fig. 1

Fig. 2a

Fig. 2b

14 Feedback
Stabilisation

Fig. 3

$y_k(5) = $ AUTO (1) & Process State
& Controller State
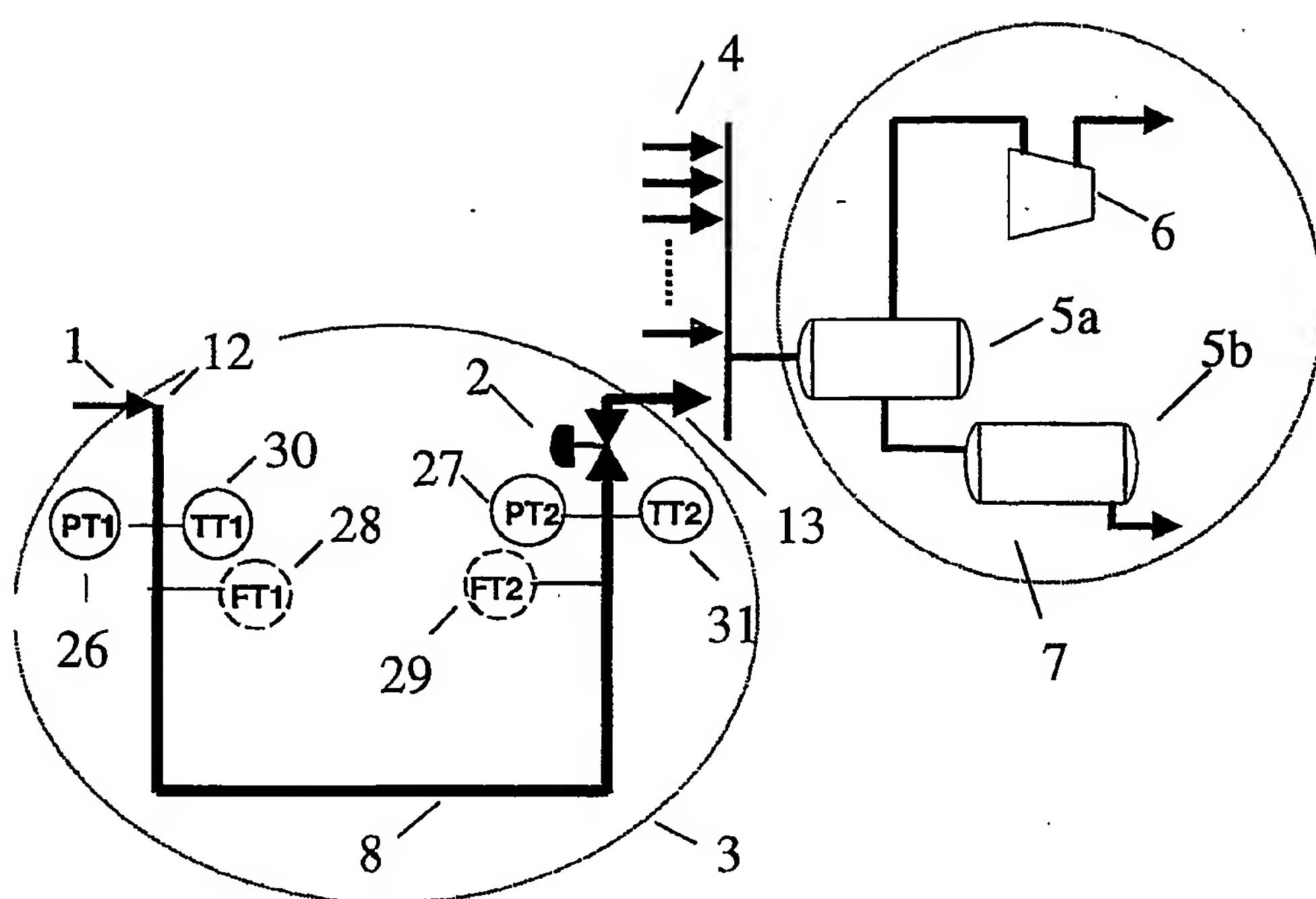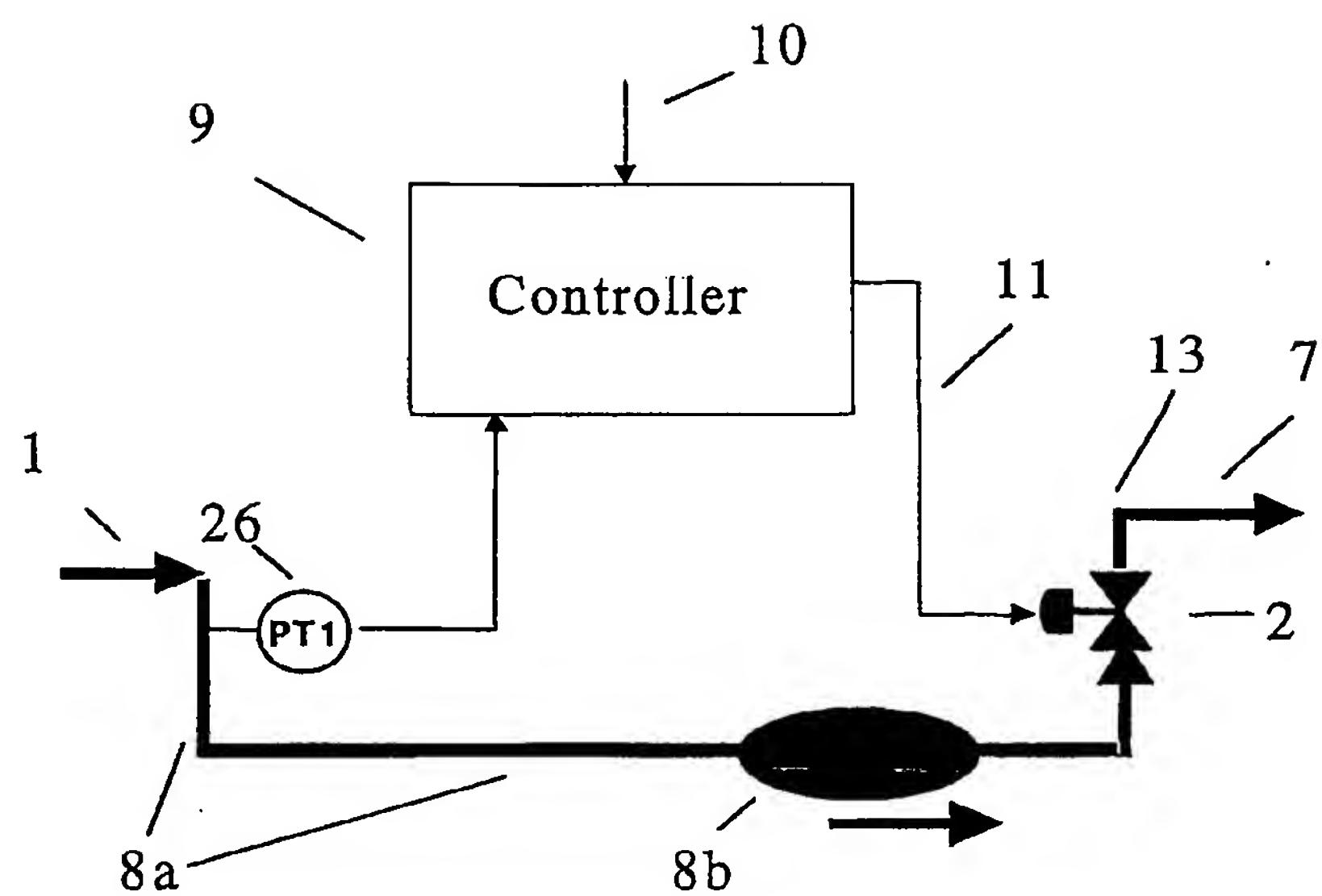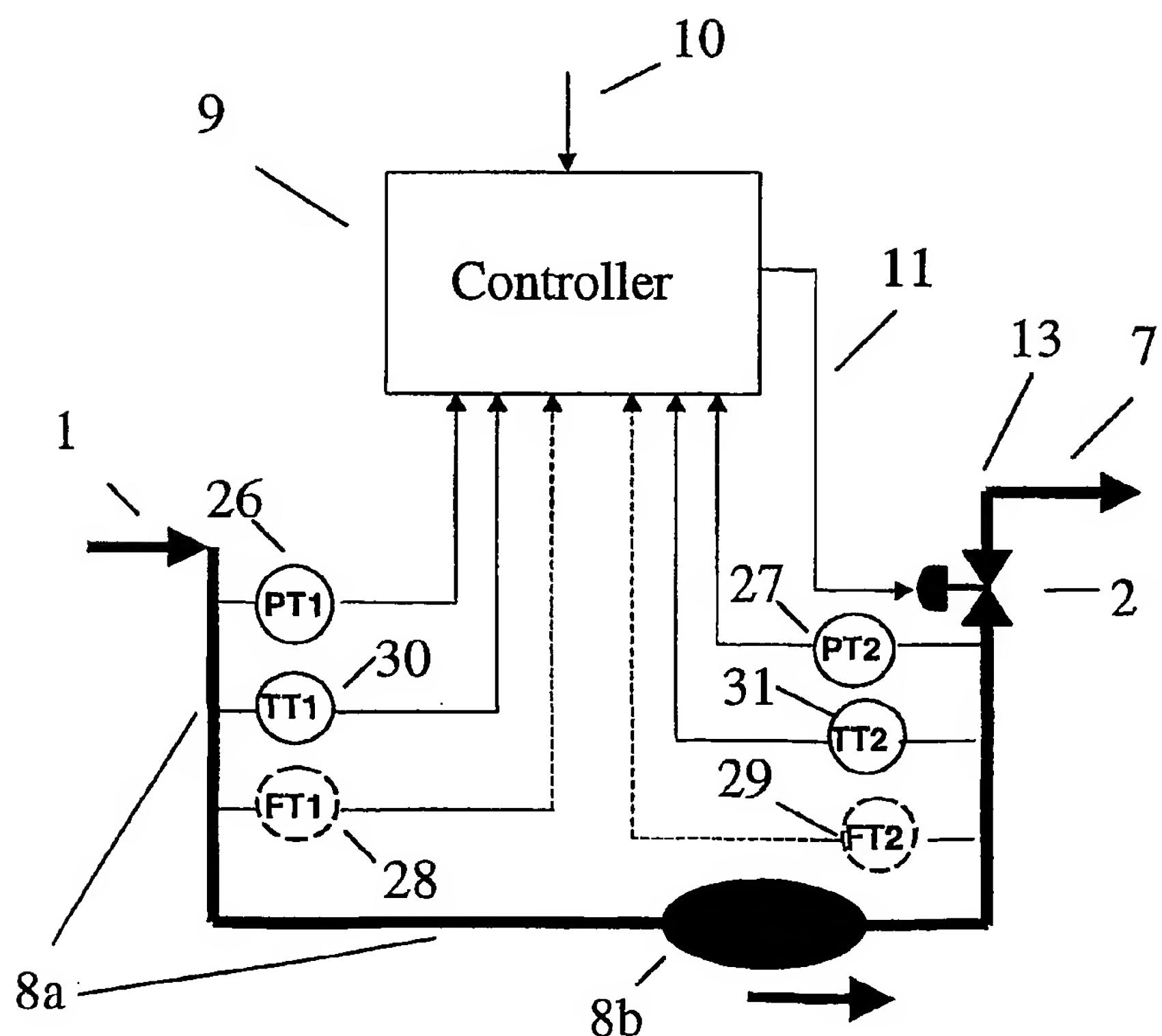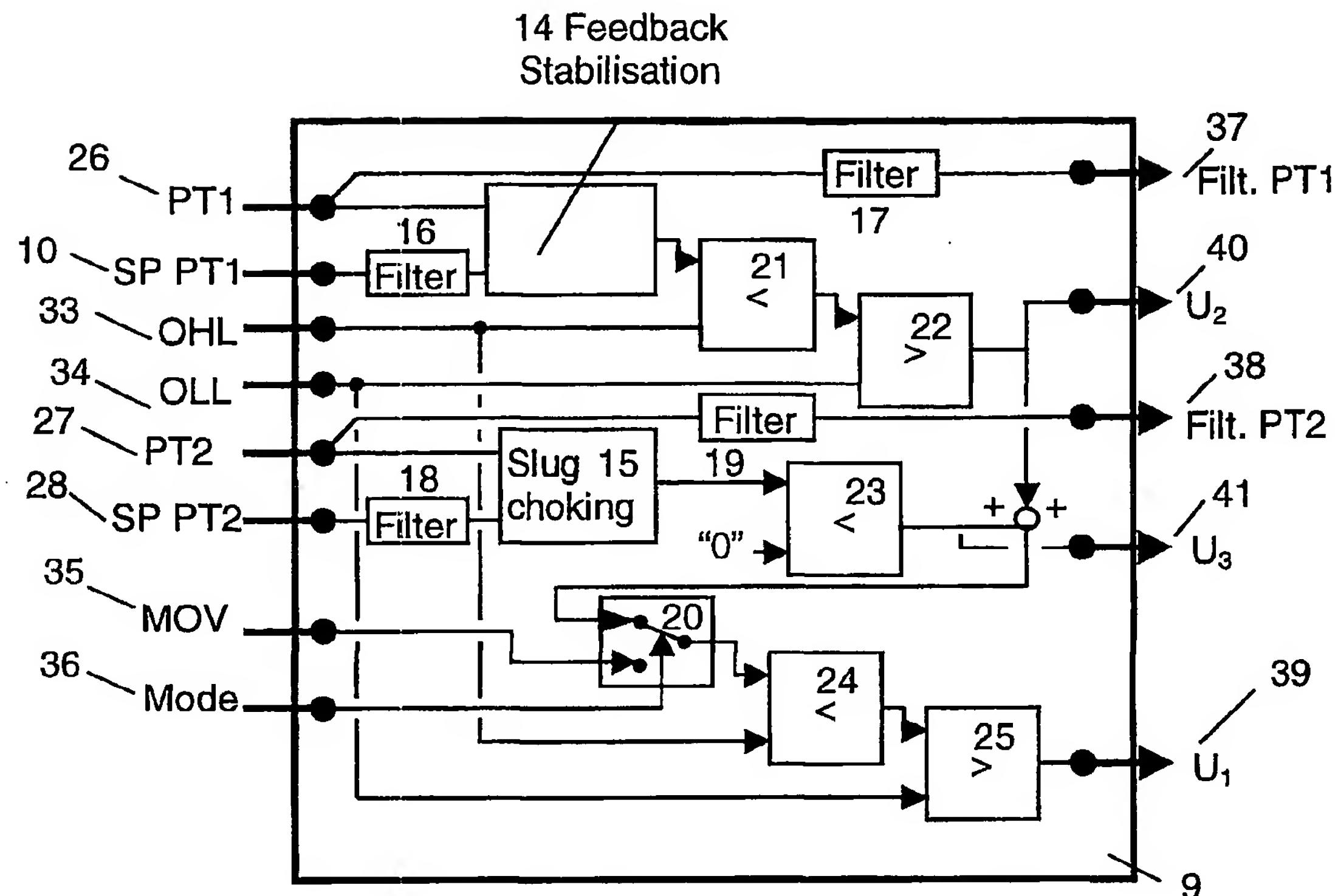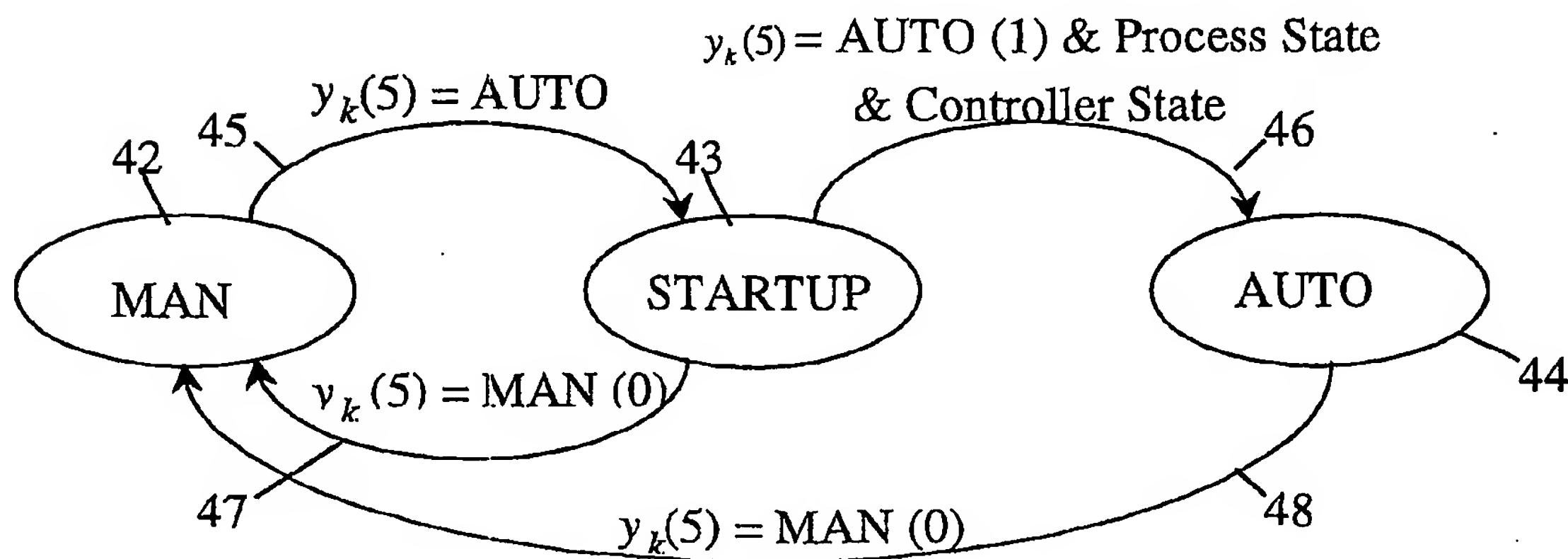
Fig. 4
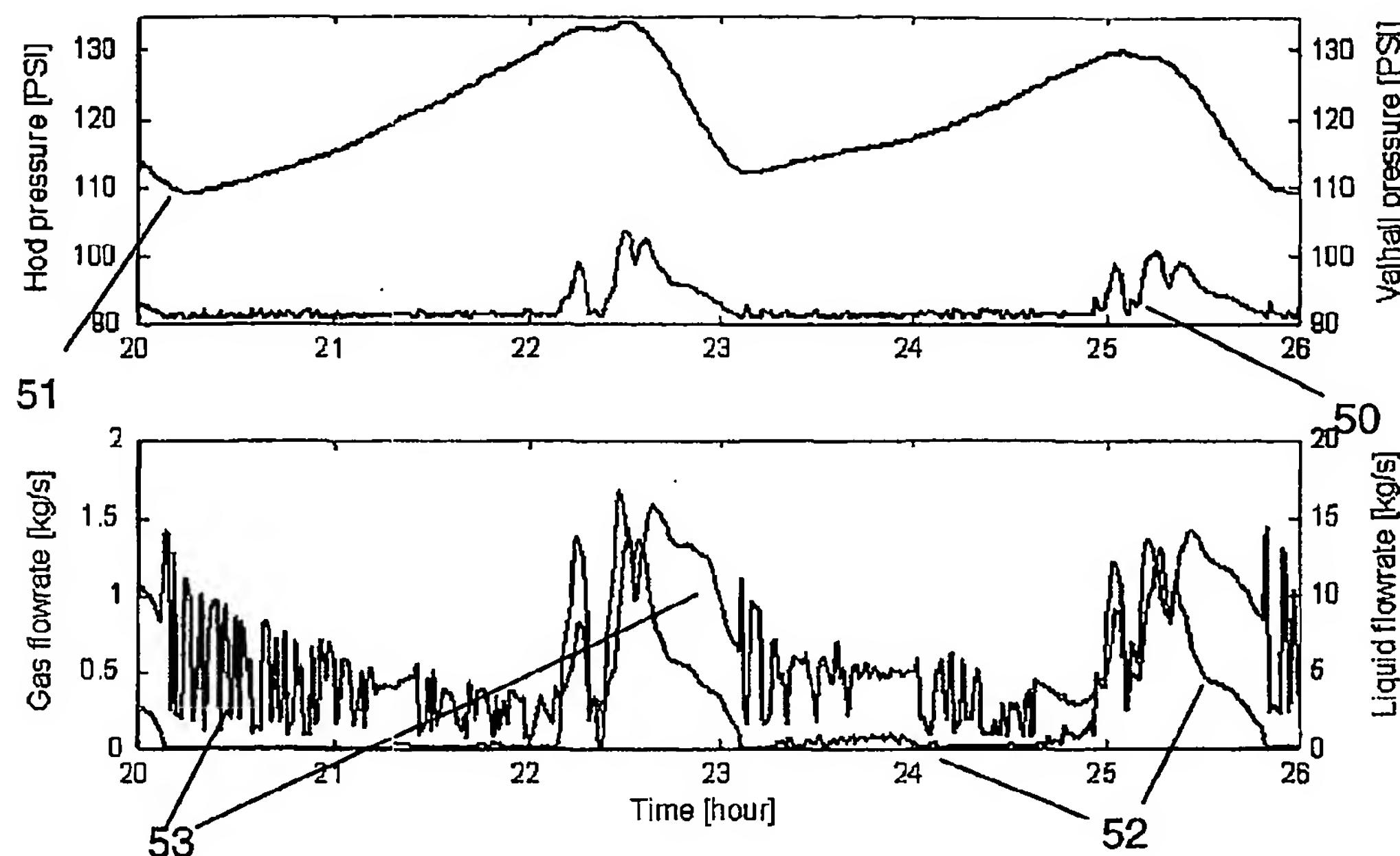
Fig. 5

Profile plot Hod - Valhall pipeline, timescope: 22h to 24h
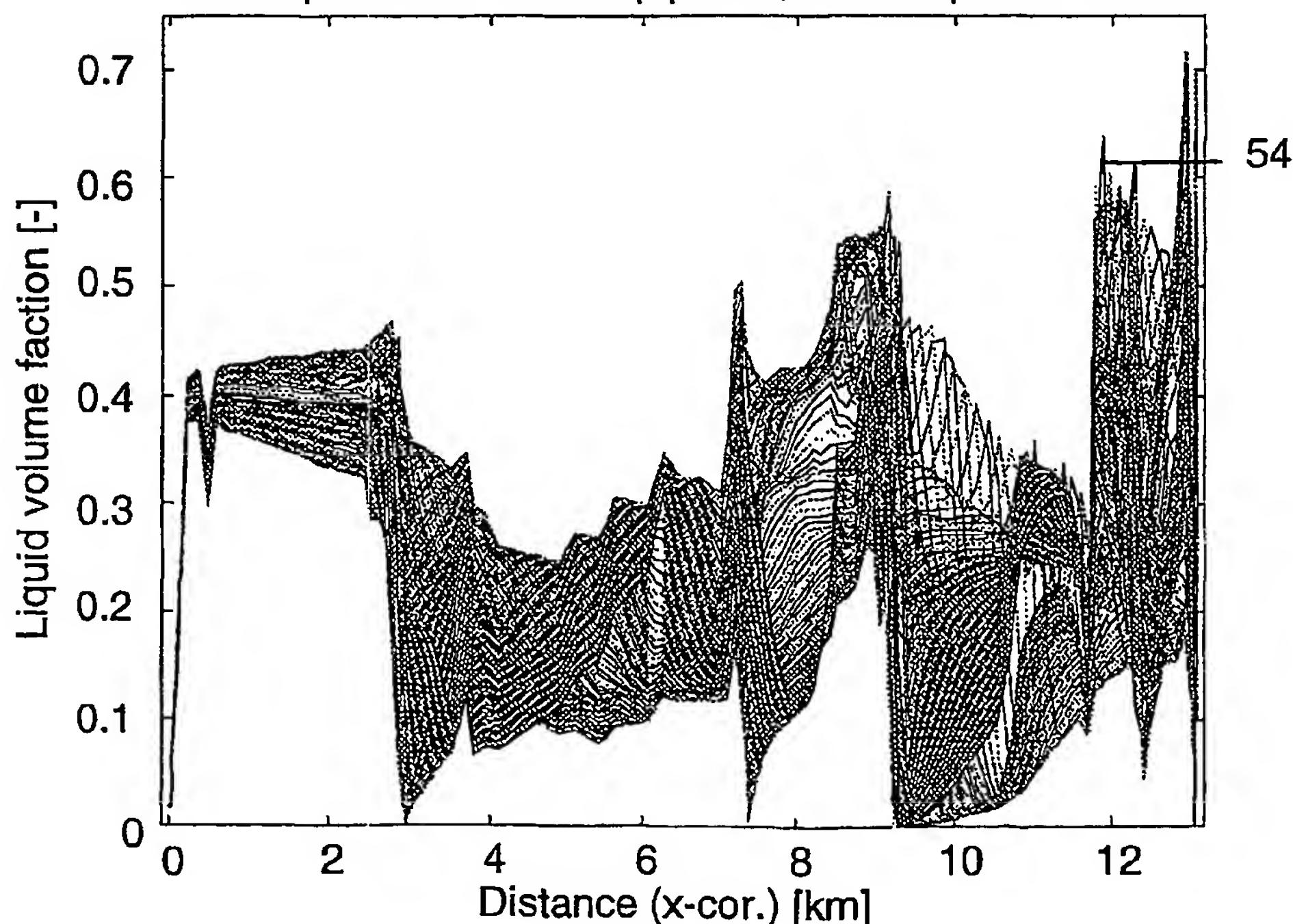
Fig. 6
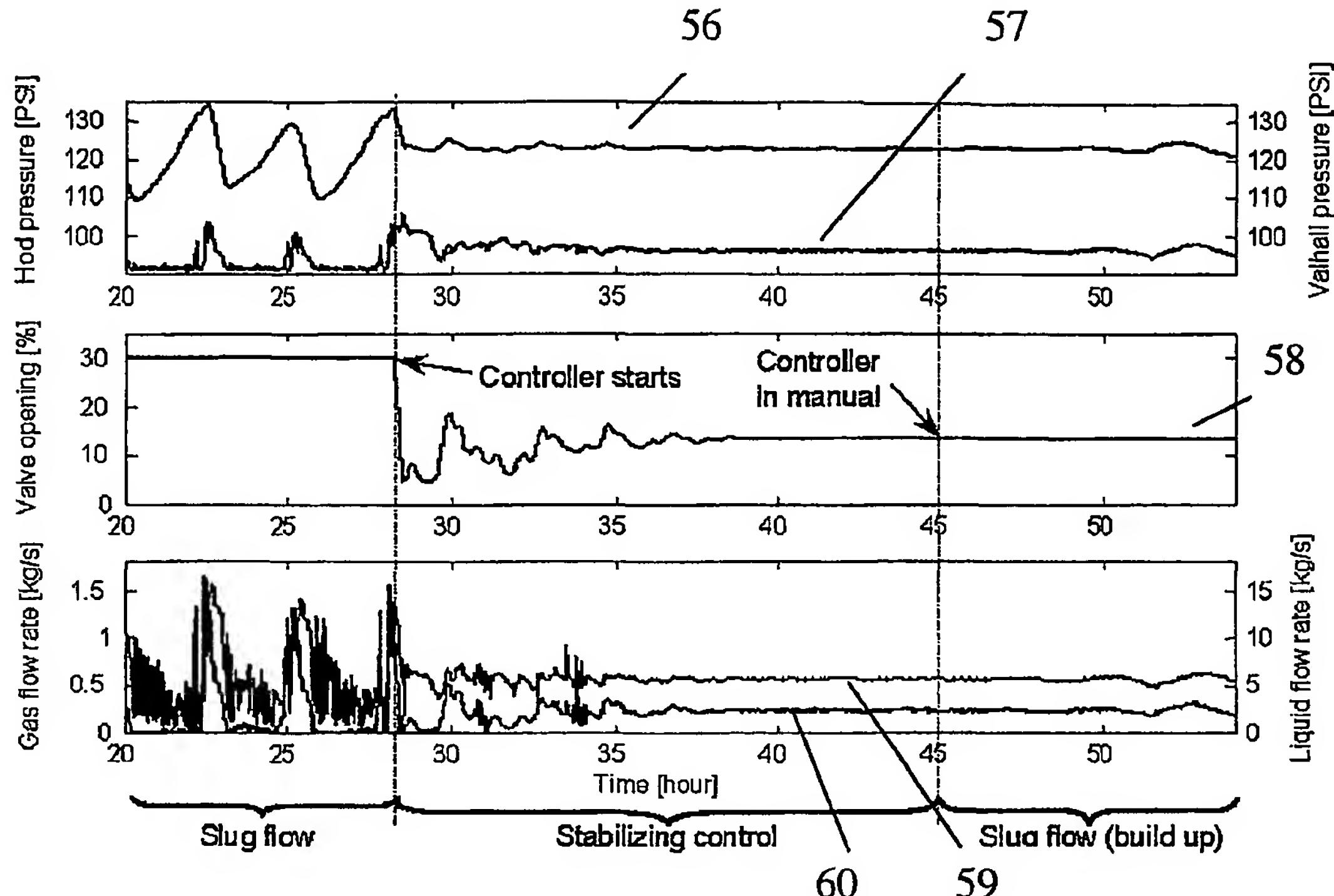
Fig. 7

Profile plot Hod - Valhall pipeline, timescope: 41h to 45h
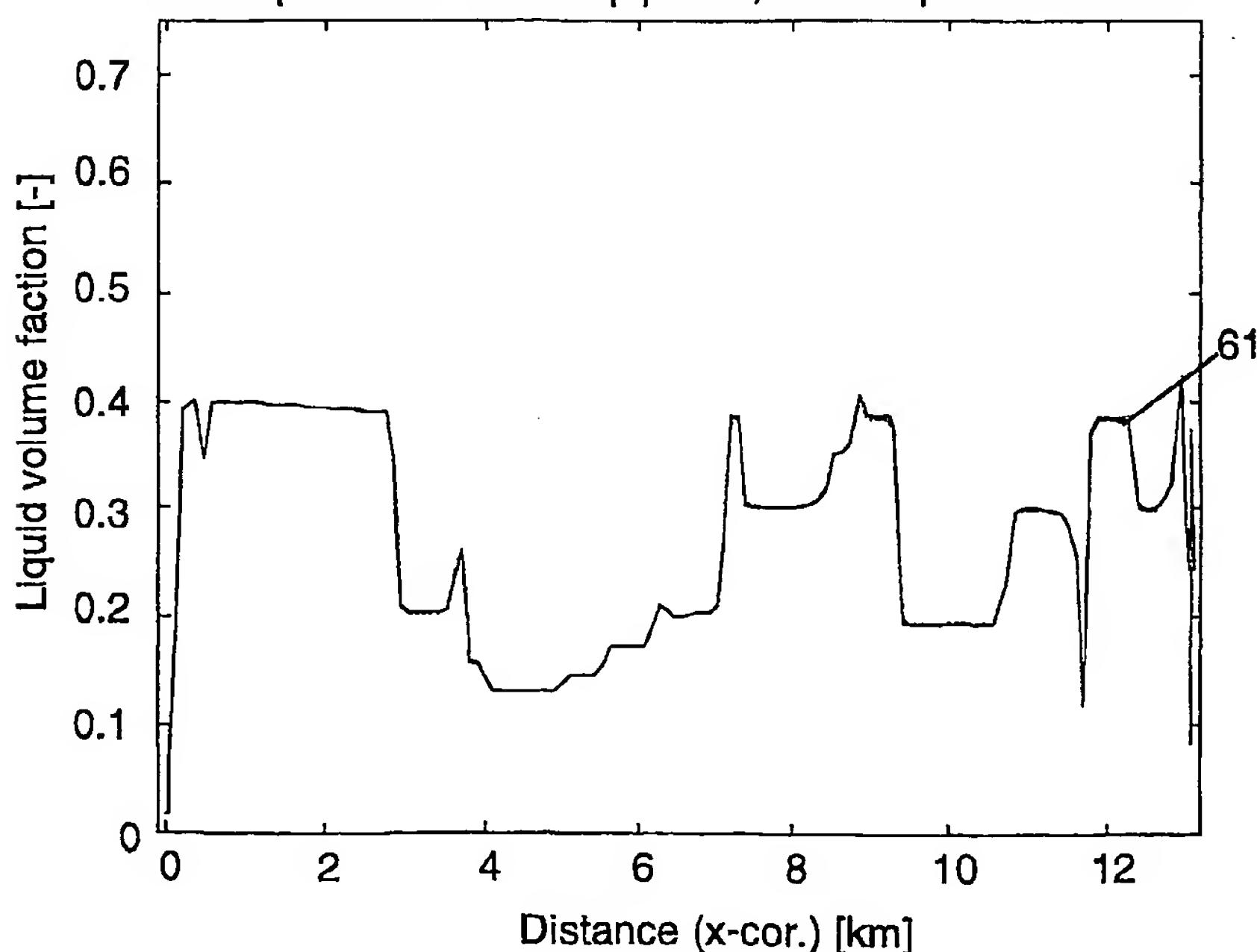
Fig. 8
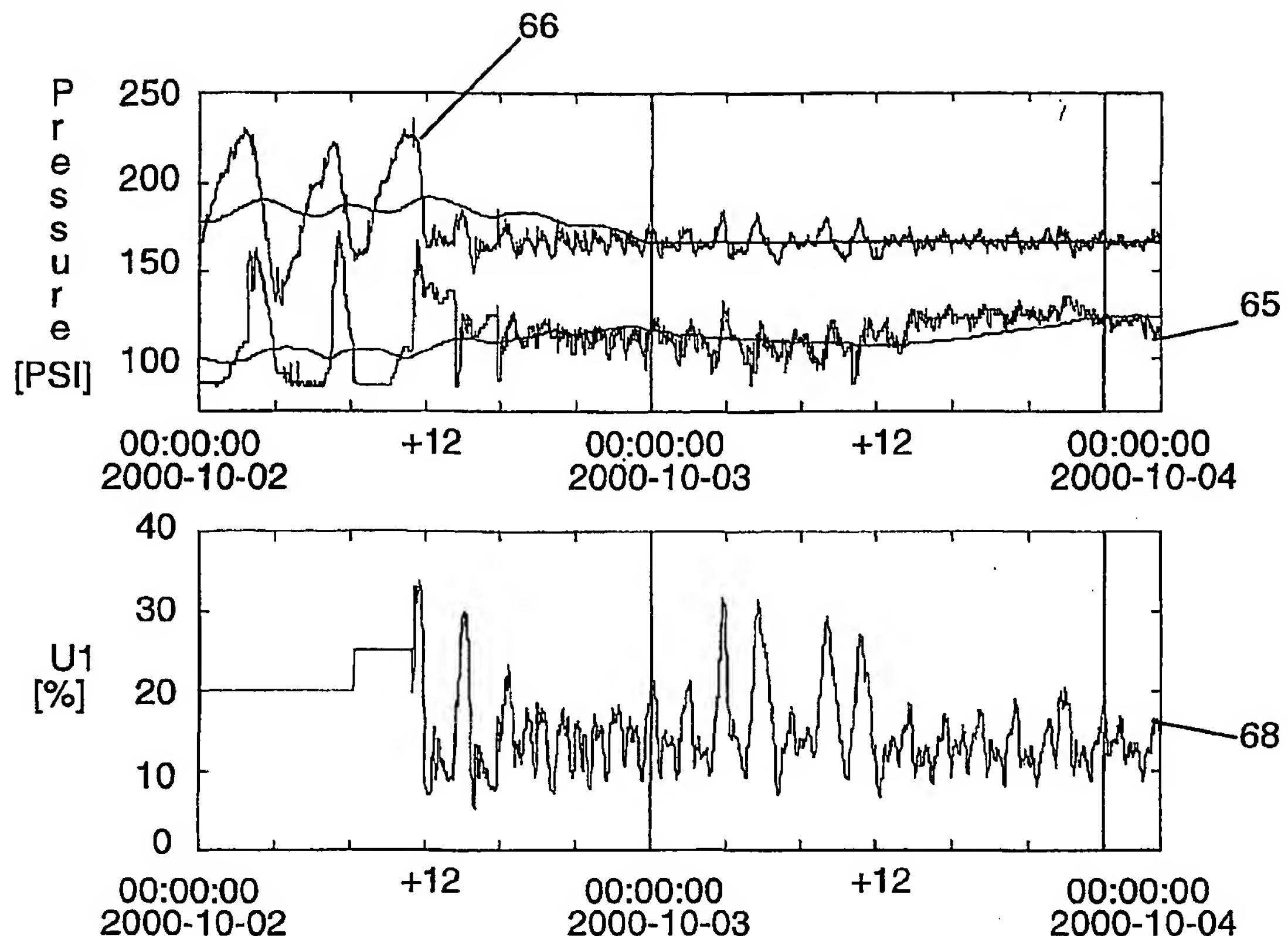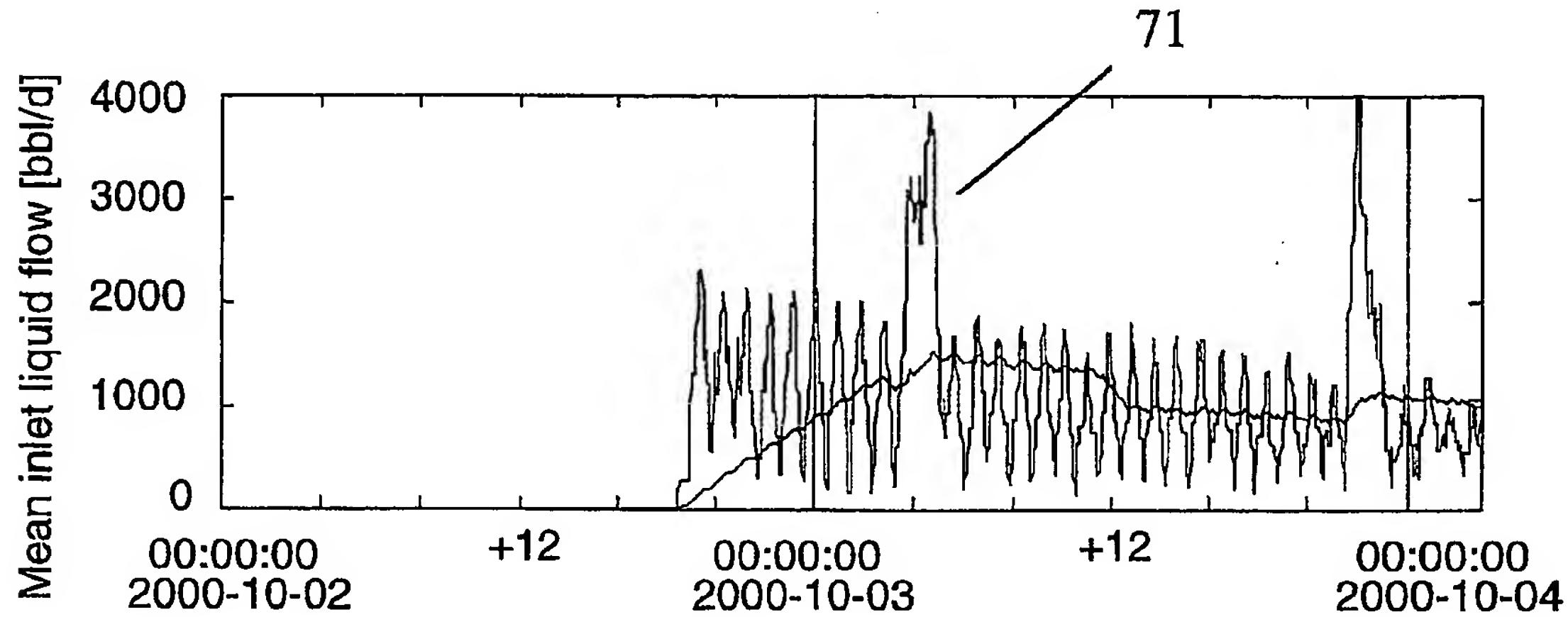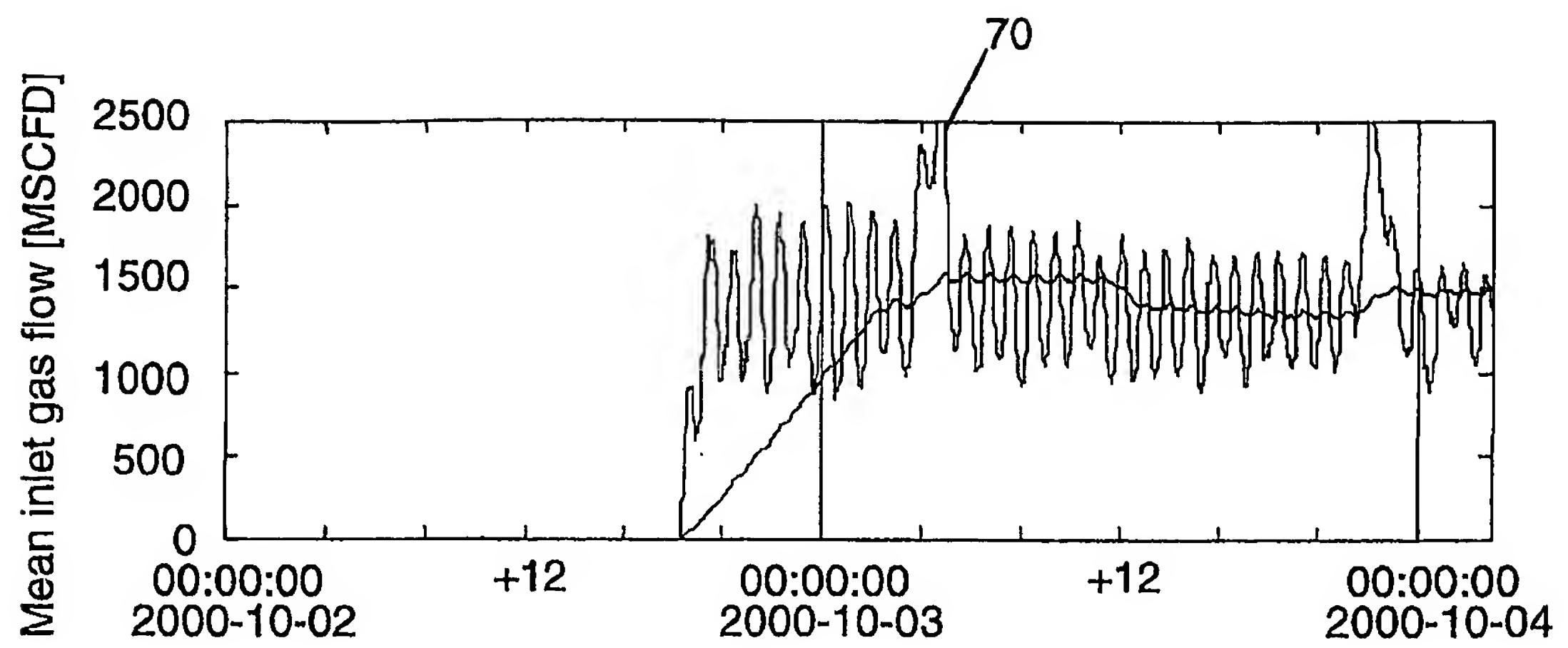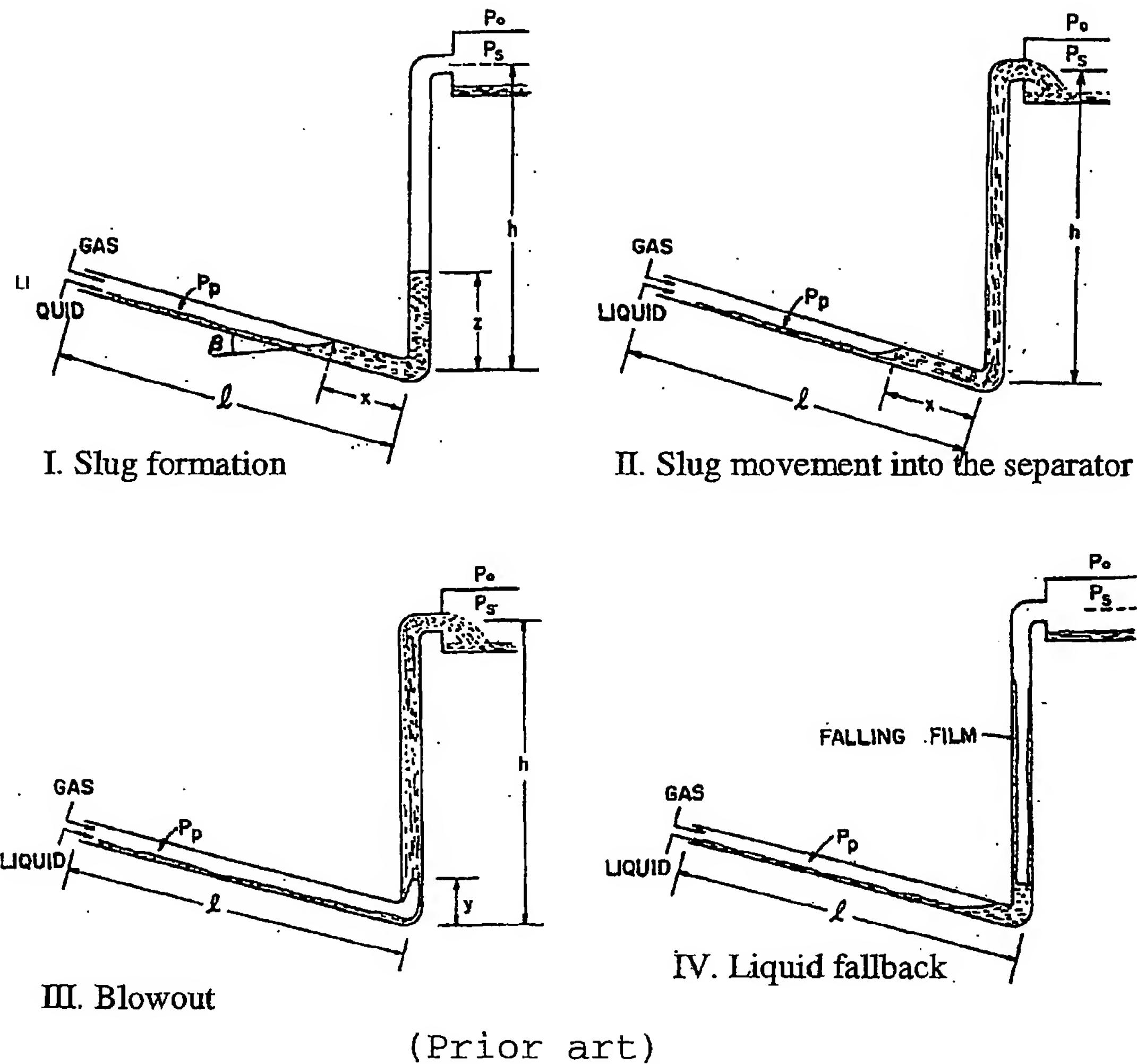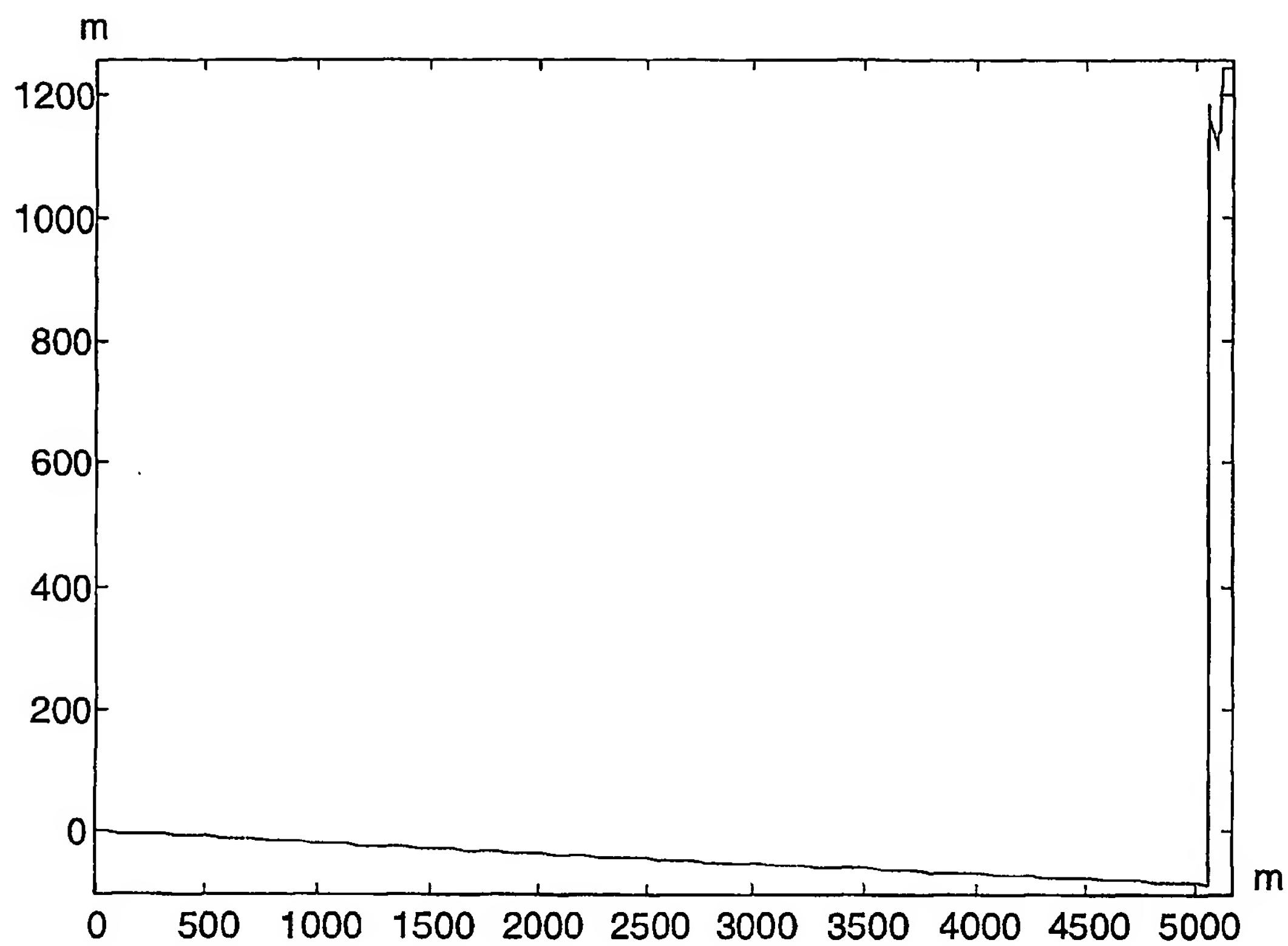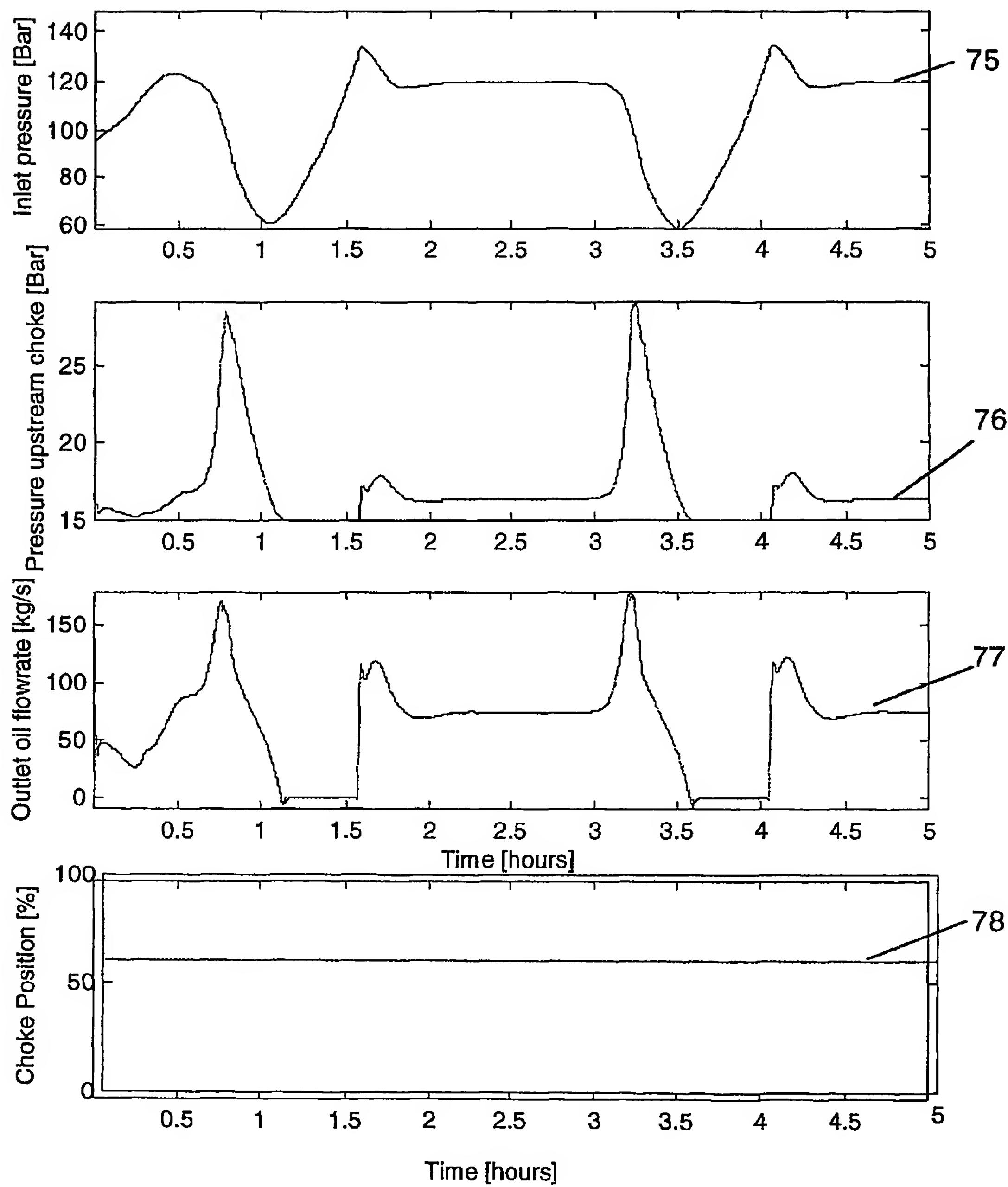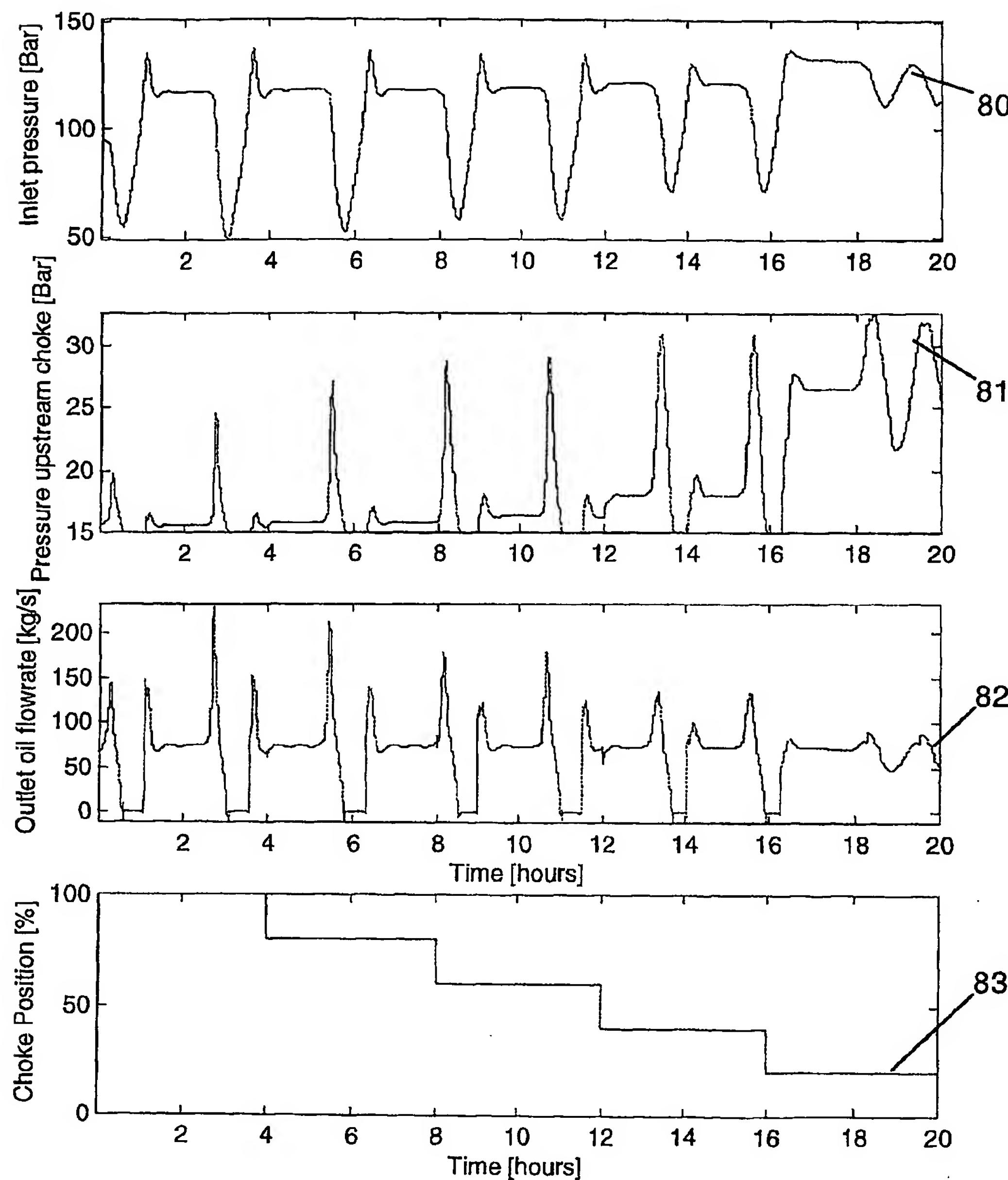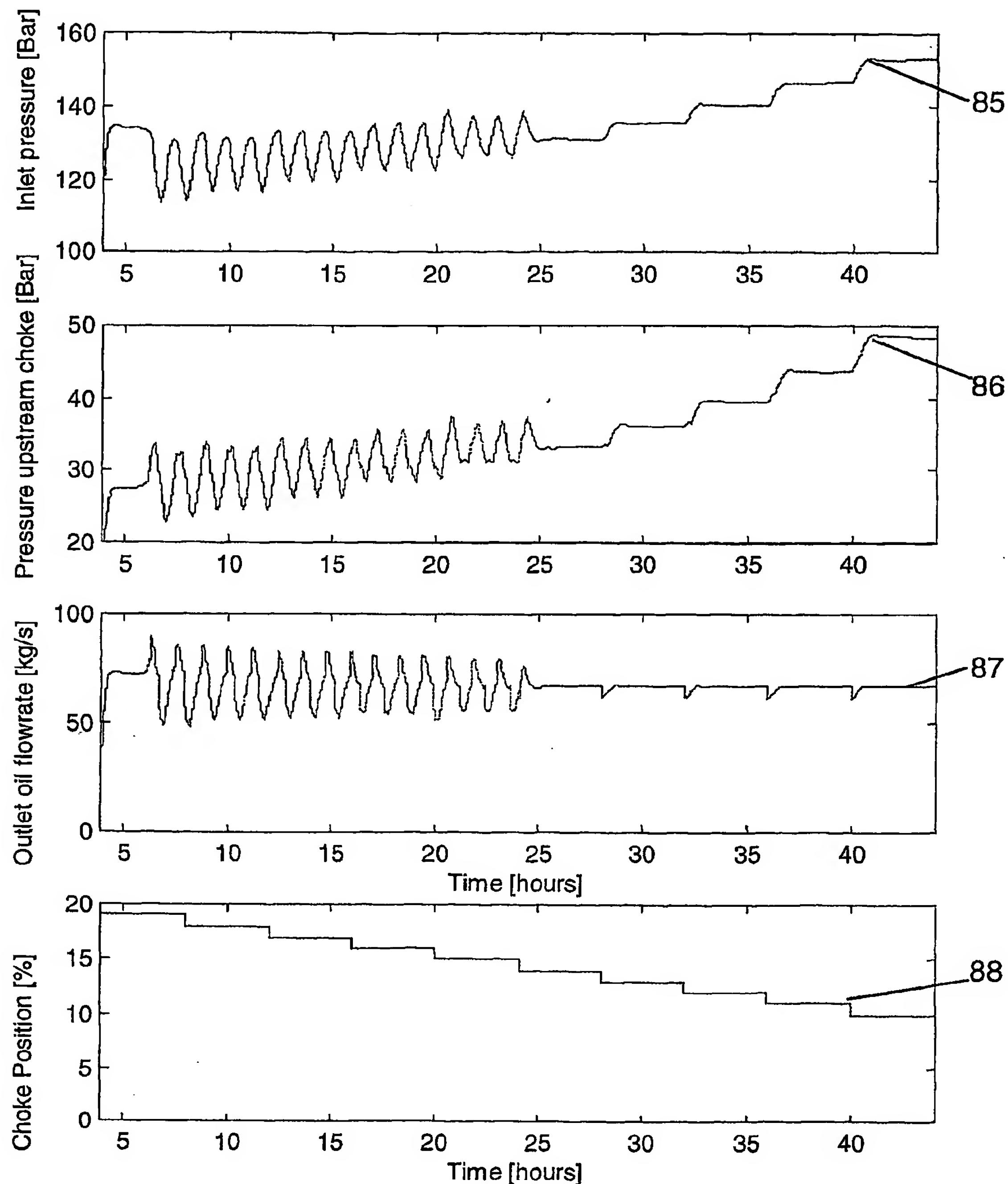
Fig. 9

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Fig. 10

I. Slug formation

II. Slug movement into the separator

III. Blowout

IV. Liquid fallback

(Prior art)

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Profile plot DT =10second, time scope 1h to 3.5h

Fig. 16

Fig. 17

Profile plot DT =10second, time scope 2h to 4.5h

95

Fig. 18

Controller in manual   Controller in auto   Controller in manual

Slug flow   Dynamic   Slug flow
                             feedback control
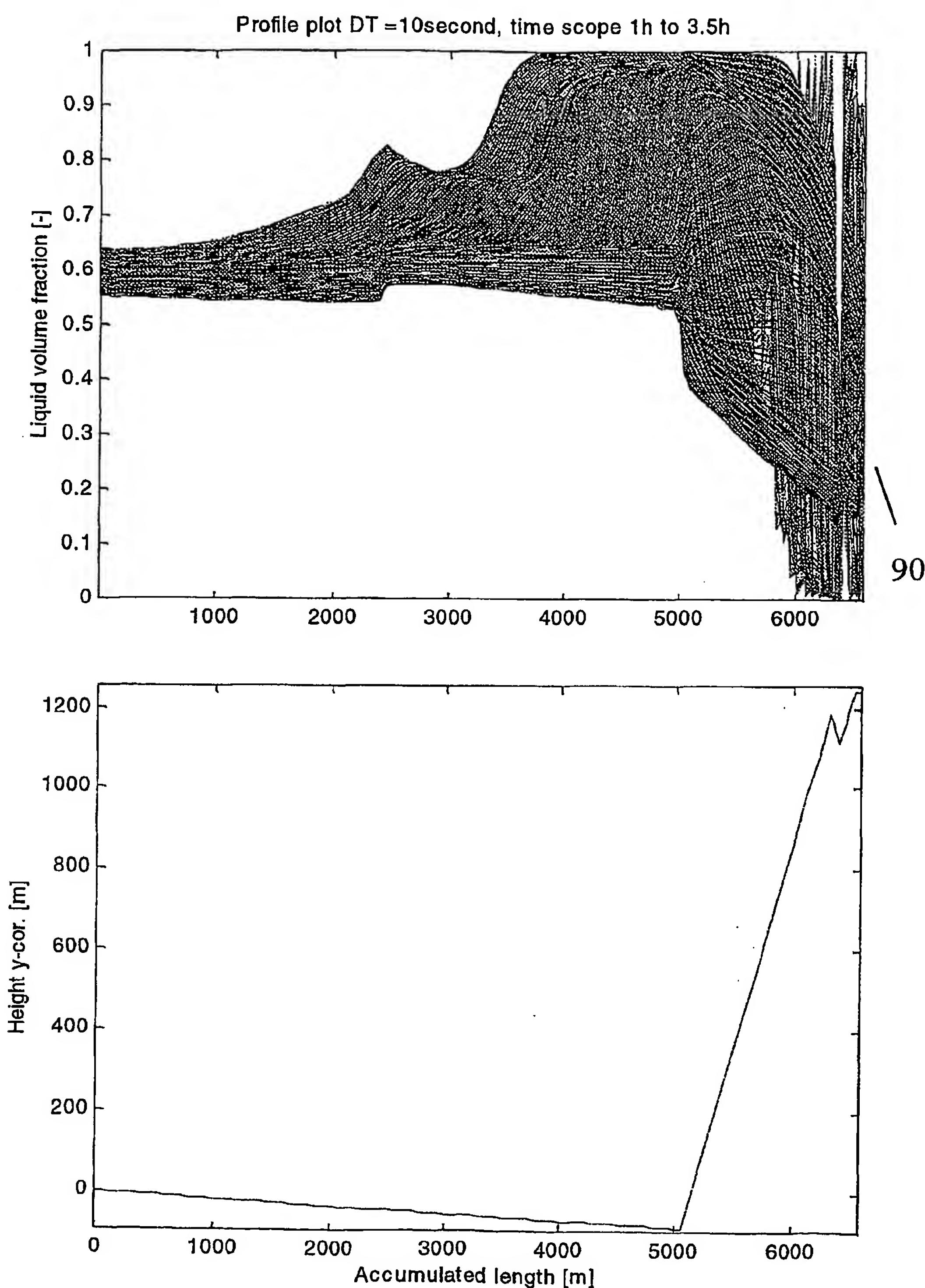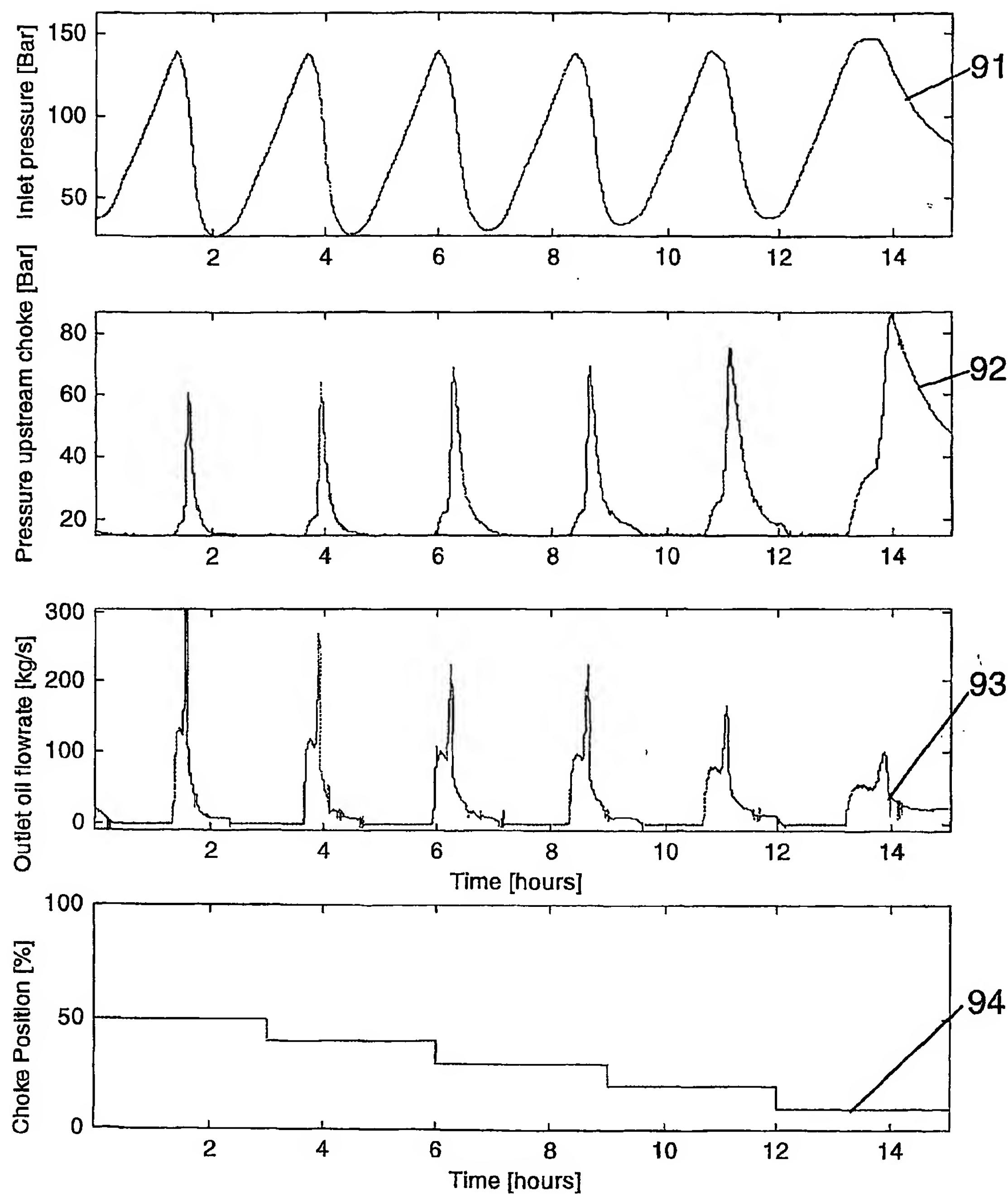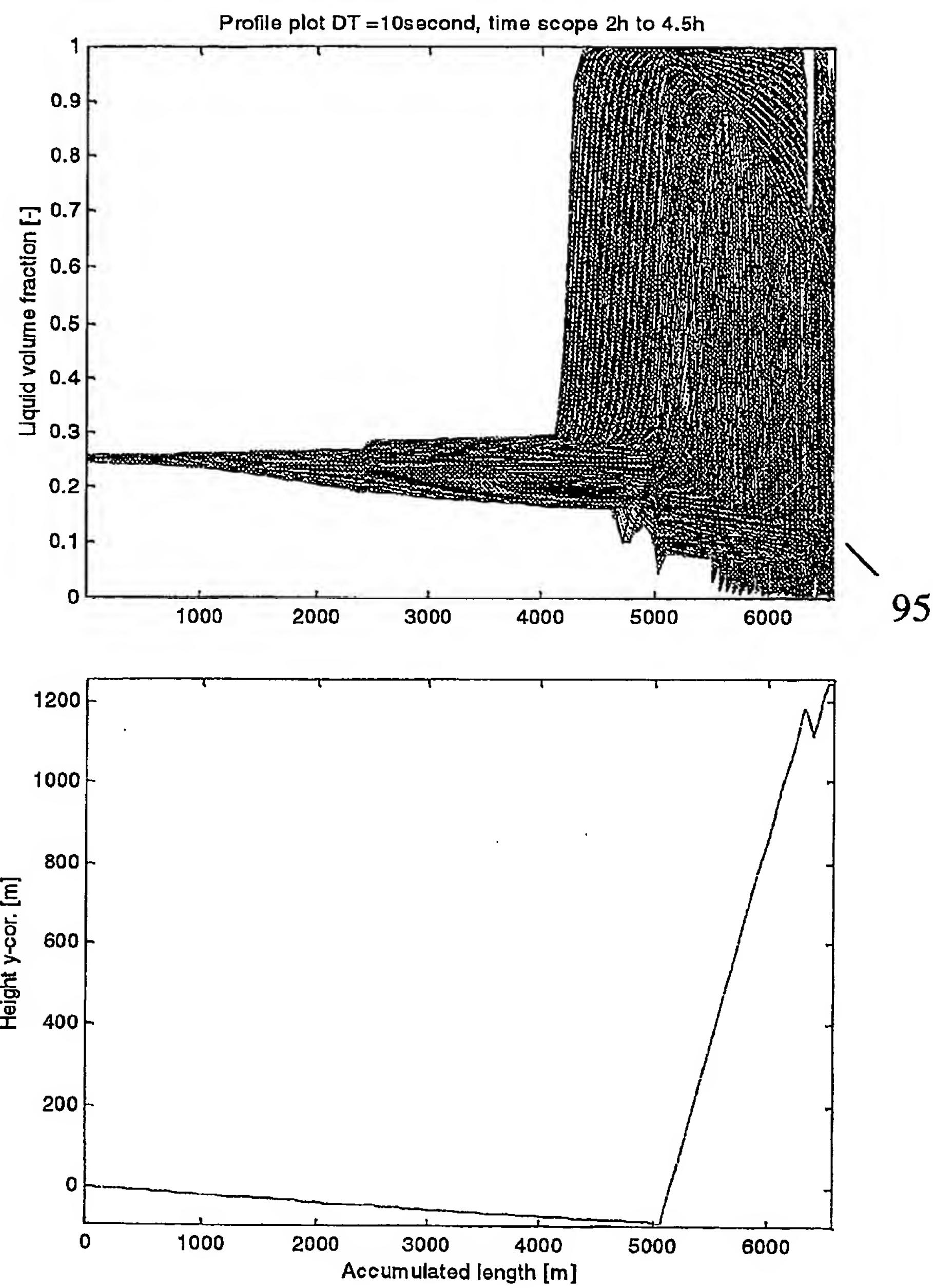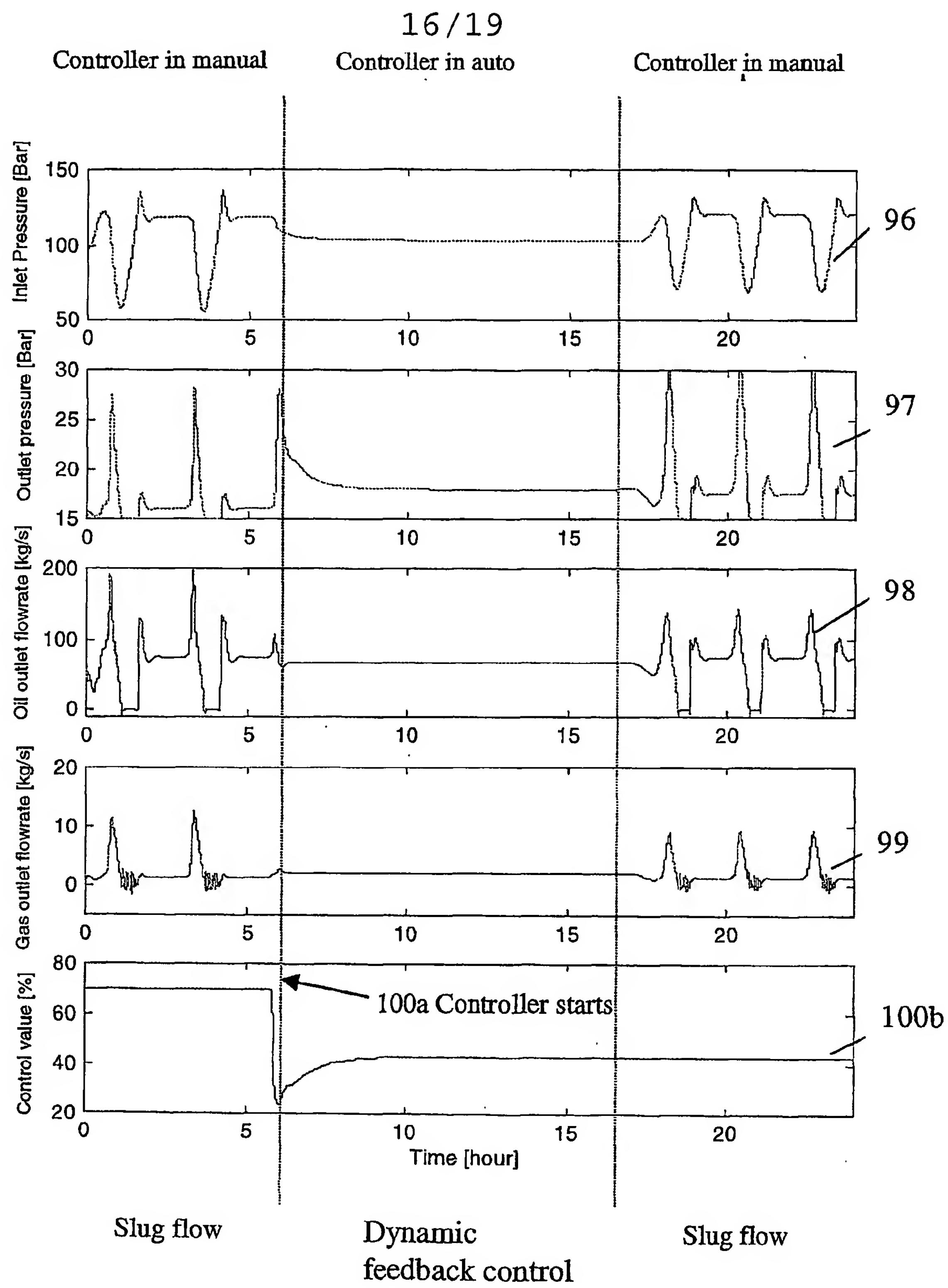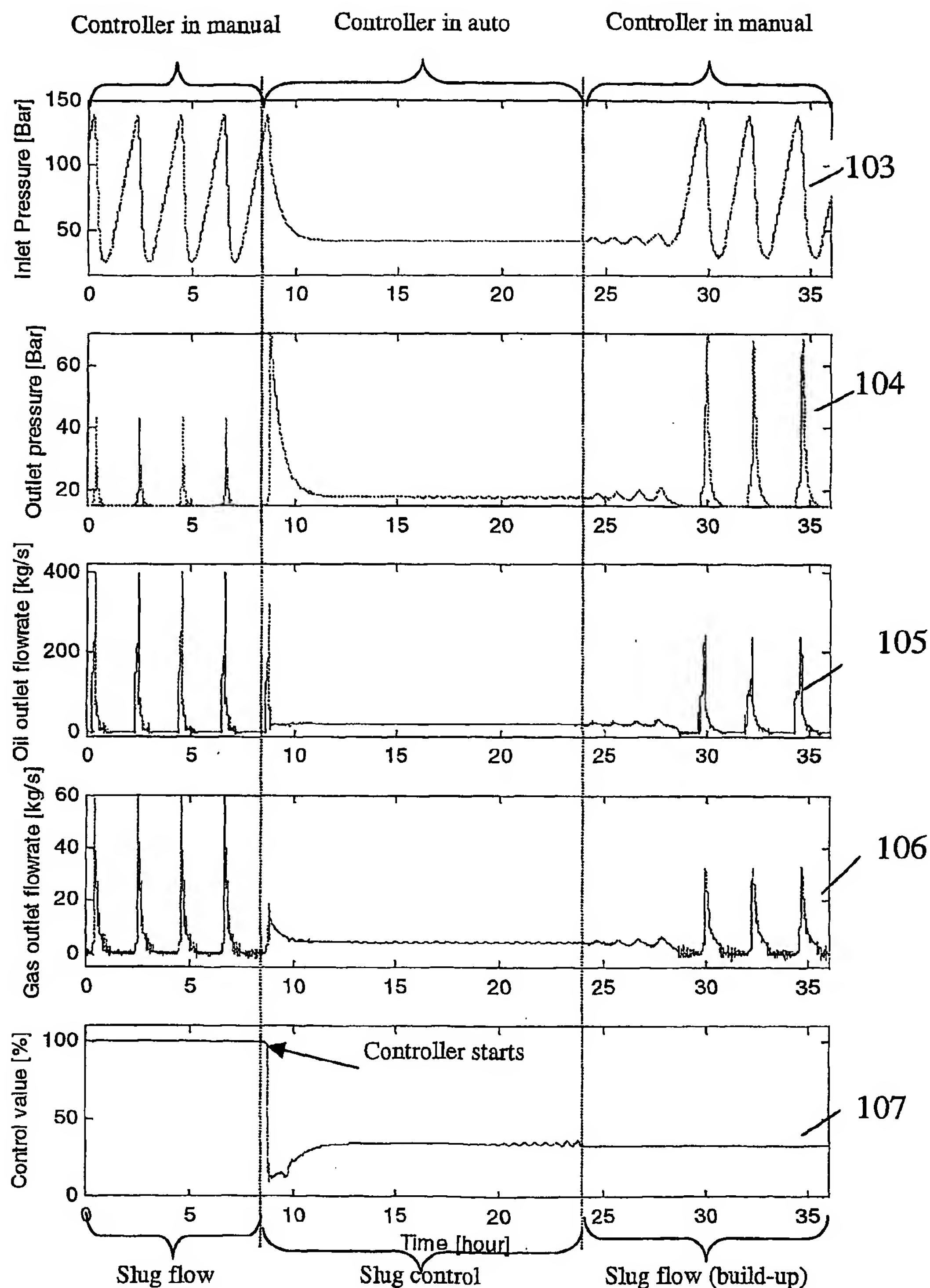
Fig. 19

Profile plot DT =10second, time scope 15h to 16h
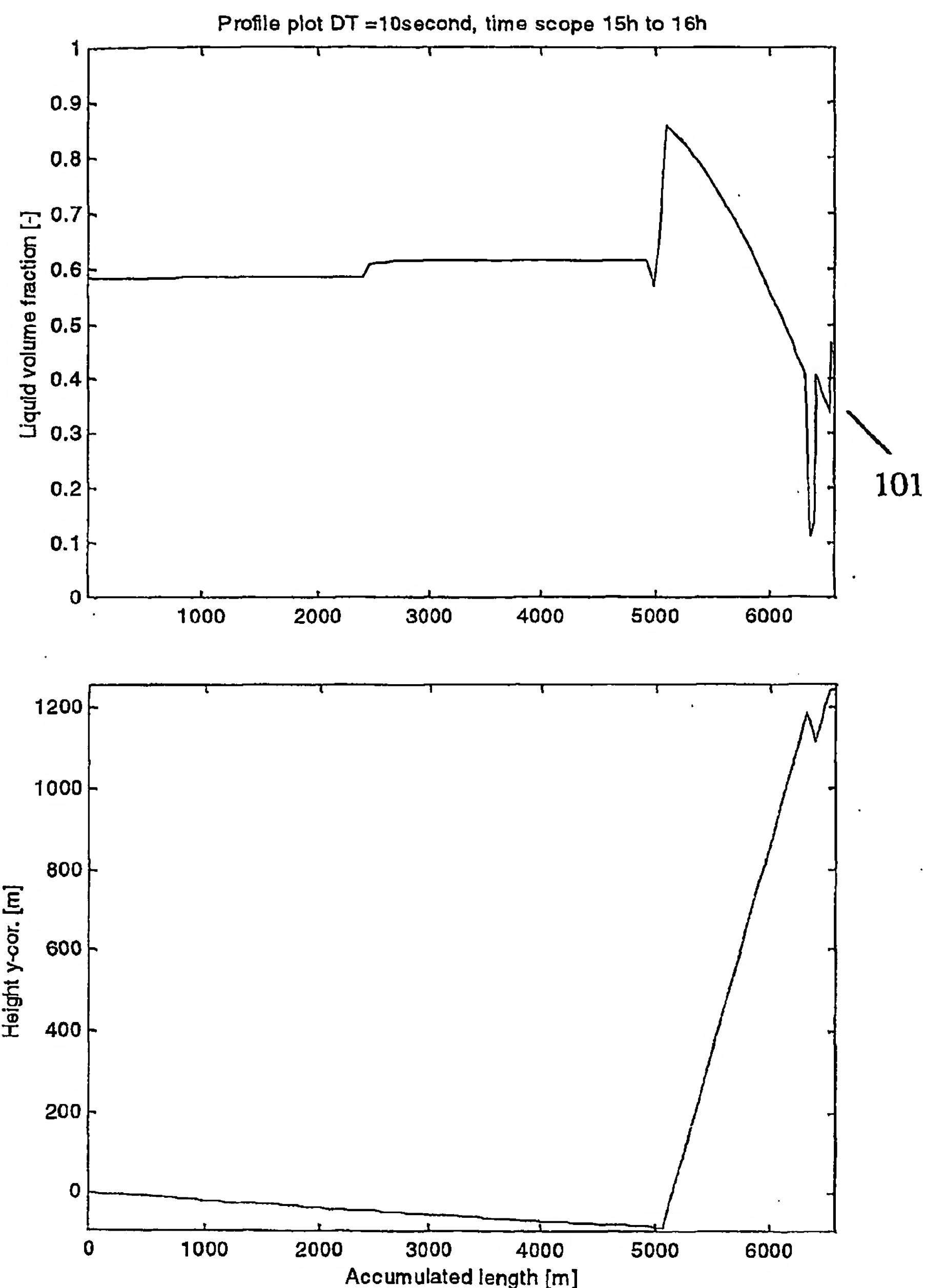

Fig. 20

Fig. 21

Profile plot DT =10second, time scope 15h to 16h
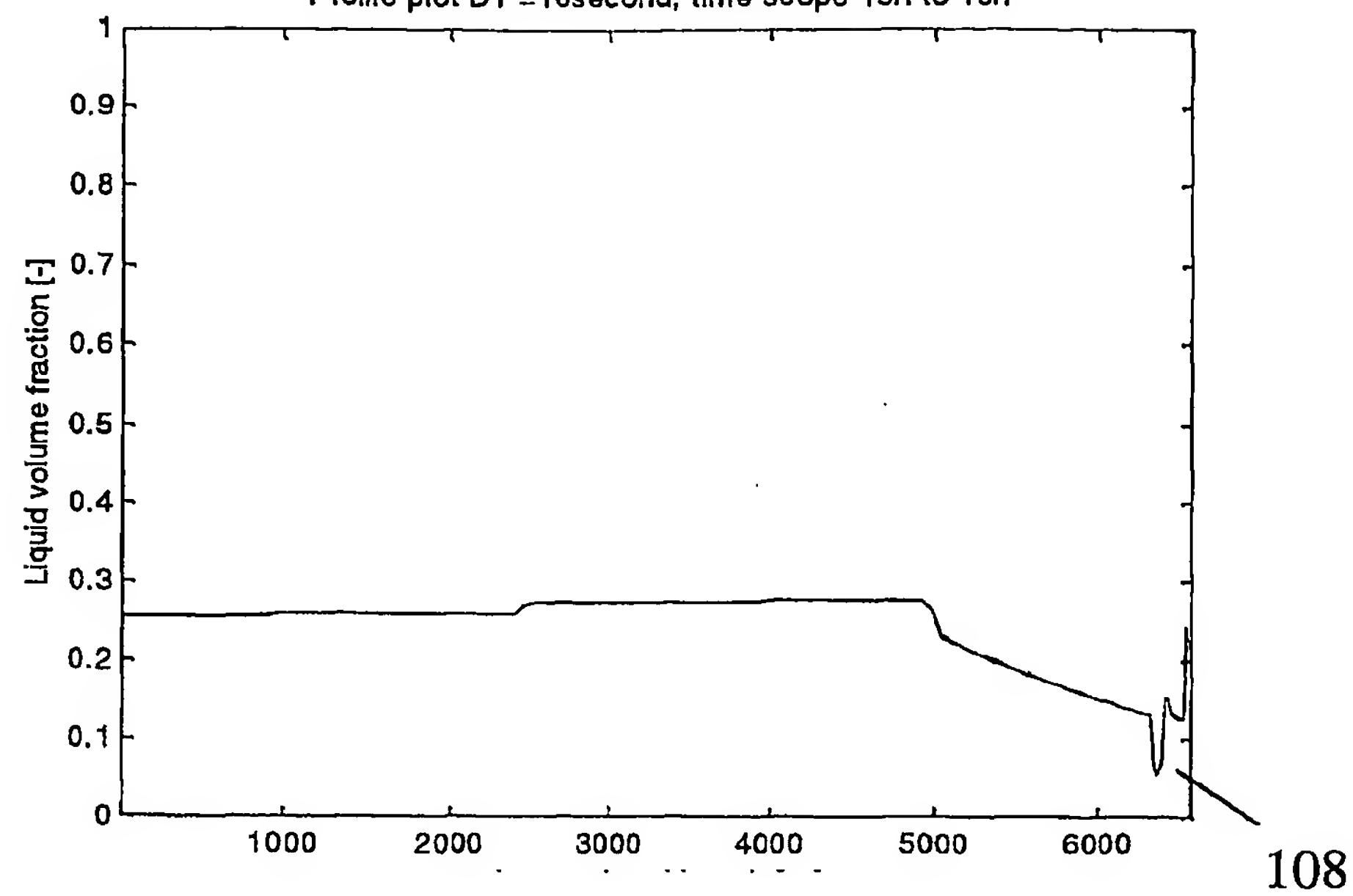
108
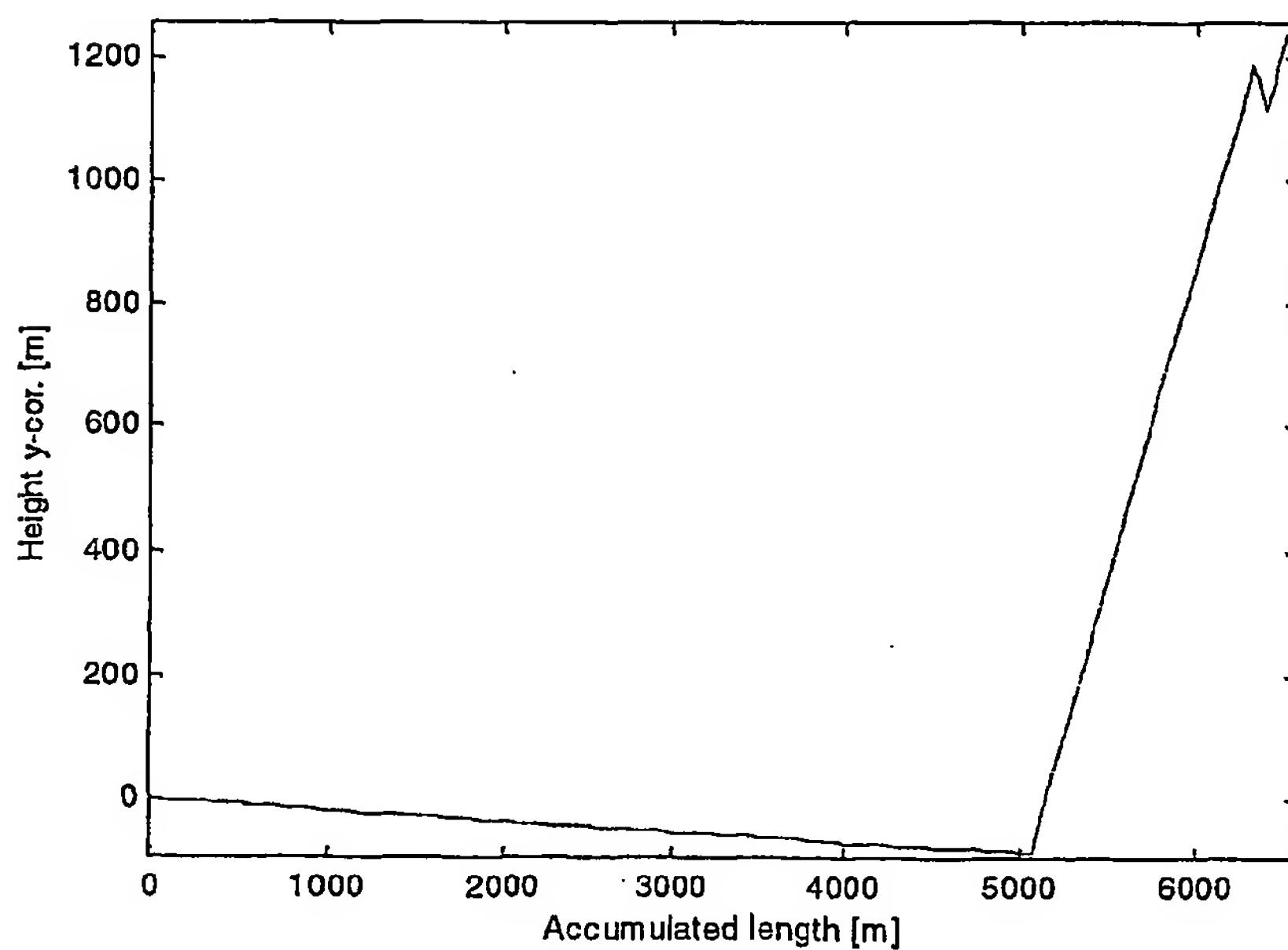
Fig. 22

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: E21B 43/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2358205 A (LATTICE INTELLECTUAL PROPERTY LTD.), 18 July 2001 (18.07.01), page 7 - page 9; page 11, figures	1,15-17,19
A	WO 0000715 A1 (ABB RESEARCH LTD.), 6 January 2000 (06.01.00)	1-19
A	US 6041803 A (A.R. DE ALMEIDA ET AL), 28 March 2000 (28.03.00)	1-19

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 March 2002	2 7 -03- 2002

Name and mailing address of the ISA/	Authorized officer
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Form PCT/ISA/210 (second sheet) (July 1998)

INTERNATIONAL SEARCH REPORT
Information on patent family members

28/01/02

Patent document cited in search report			Publication date	Patent family member(s)			Publication date
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				GB	0000945	D	00/00/00
				GB	0013331	D	00/00/00
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				GB	0031573	D	00/00/00
				GB	2355767	A	02/05/01
				NO	982973	D	00/00/00
				NO	20006610	A	26/02/01
US	6041803	A	28/03/00	AU	6072699	A	10/04/00
				BR	9913875	A	27/11/01
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				GB	9820277	D	00/00/00
				NO	20011315	A	18/05/01
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